Recent BAO observations and plans for the future

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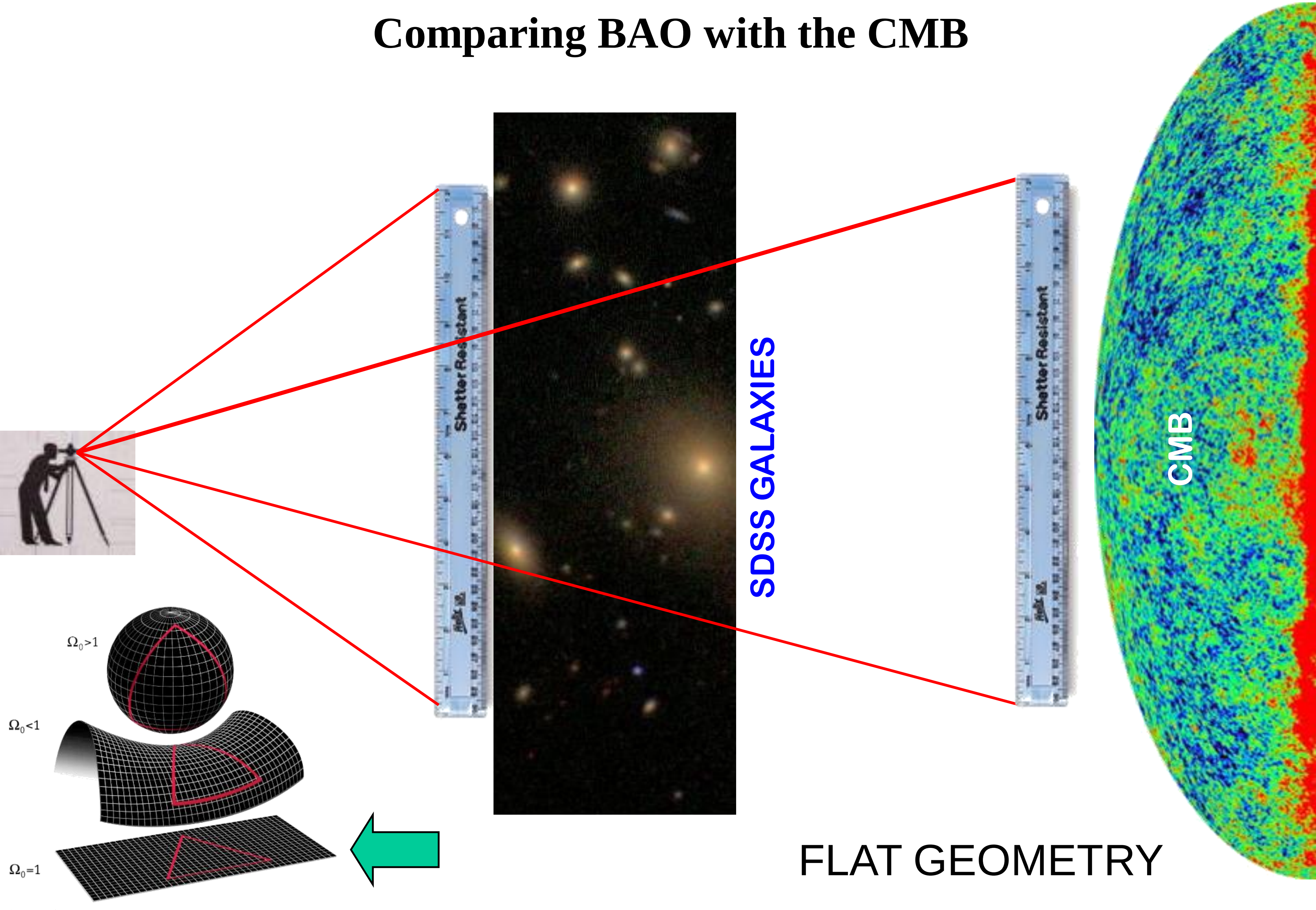
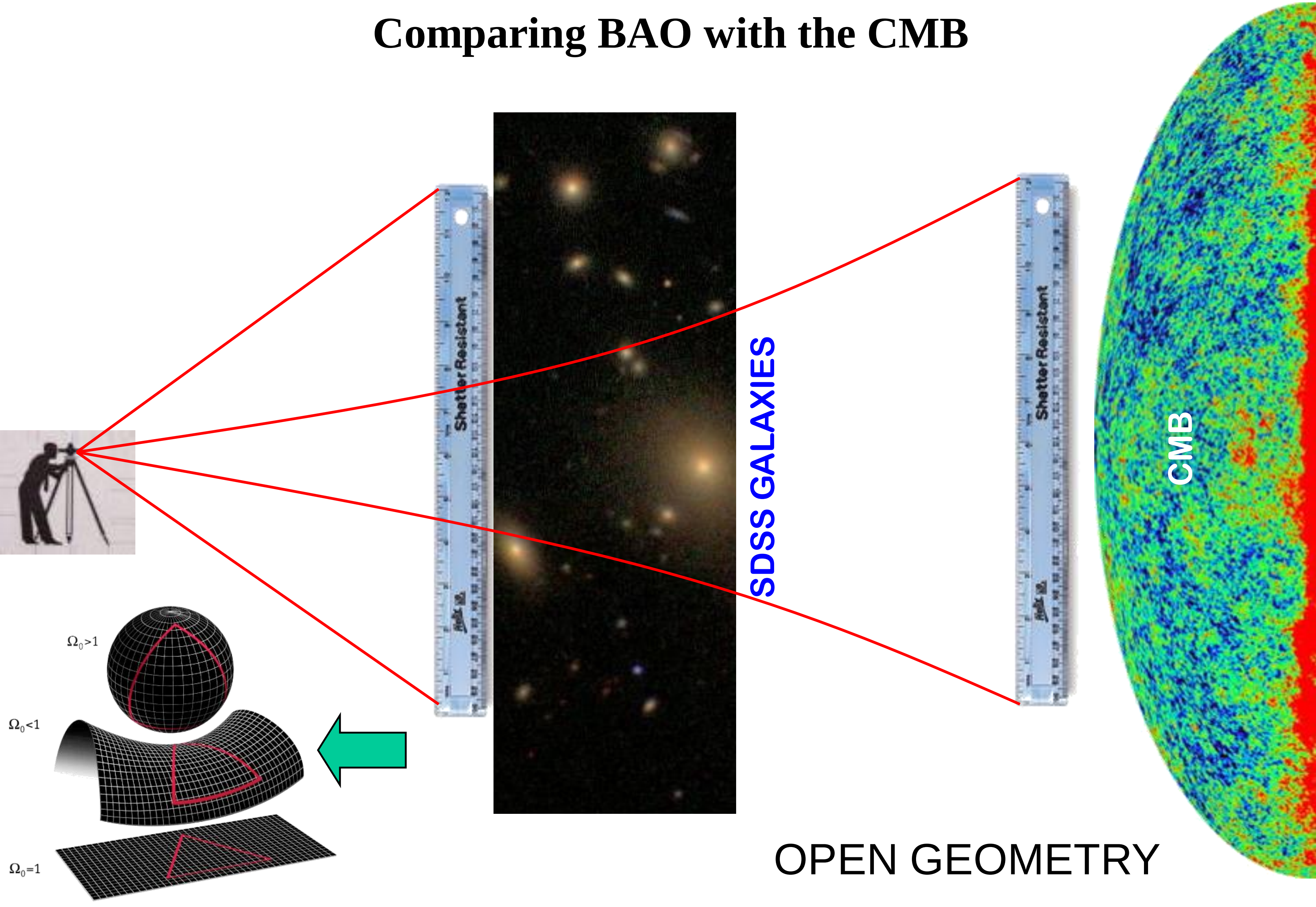
Baryon Acoustic Oscillations

Comparing BAO with the CMB



CREDIT: WMAP & SDSS websites

Comparing BAO with the CMB



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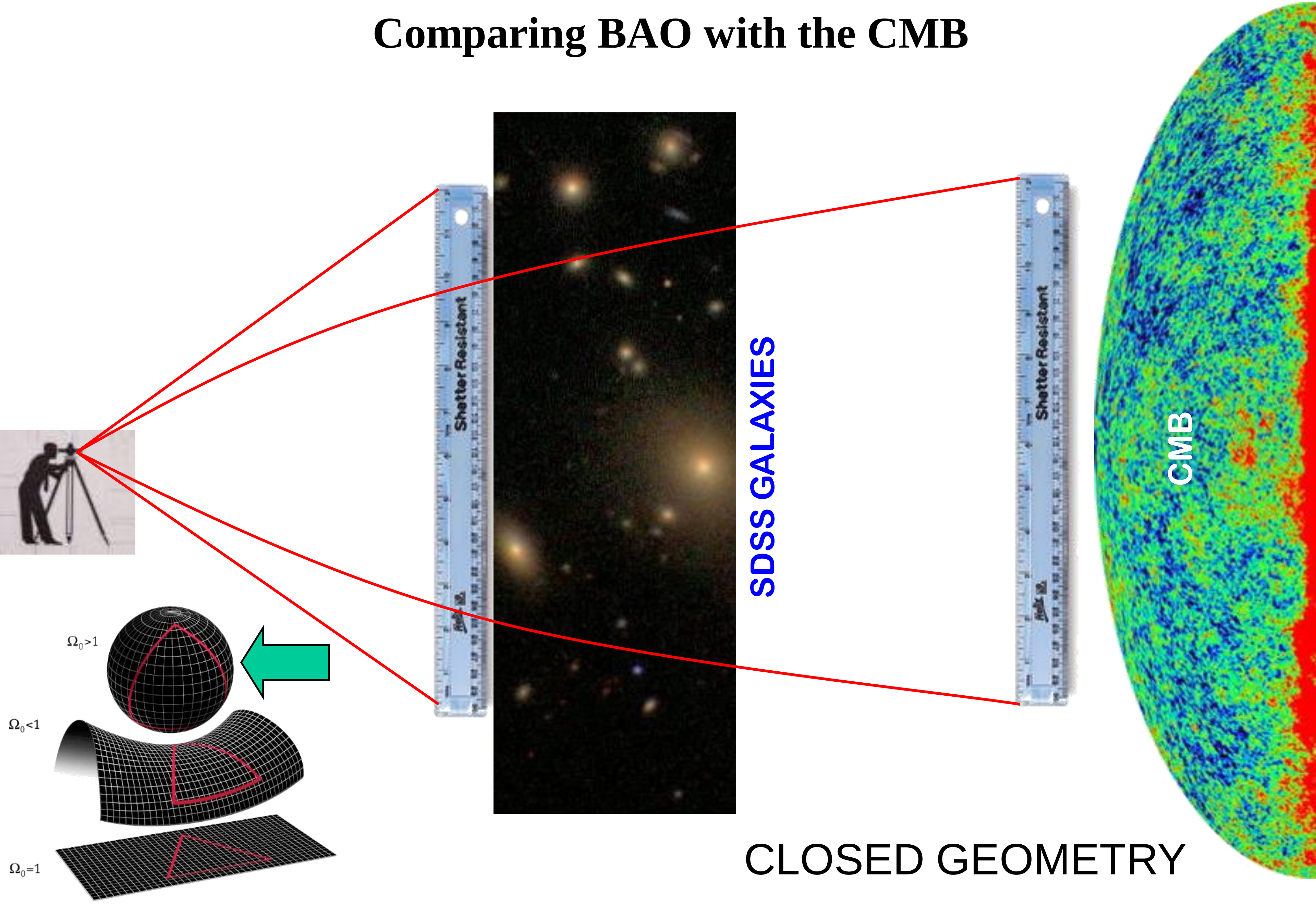
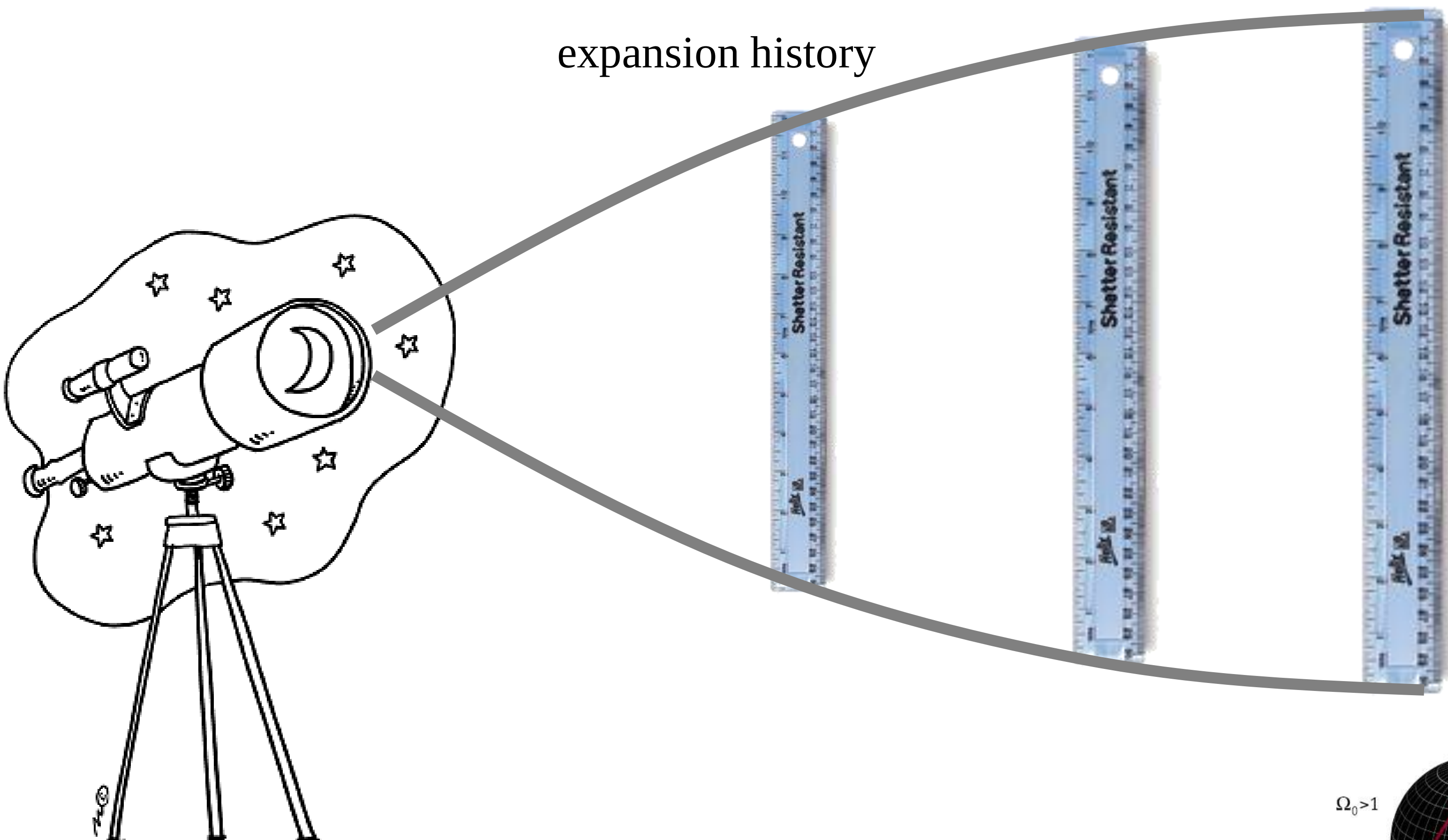
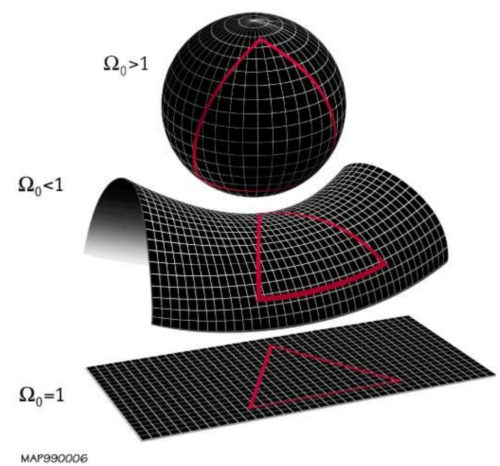
Comparing BAO with the CMB



CREDIT: WMAP & SDSS websites

Baryon features as a standard ruler





Blake & Glazebrook, 2003, ApJ, 594,665
Seo & Eisenstein, 2003, ApJ, 598, 720

Baryon features as a standard ruler

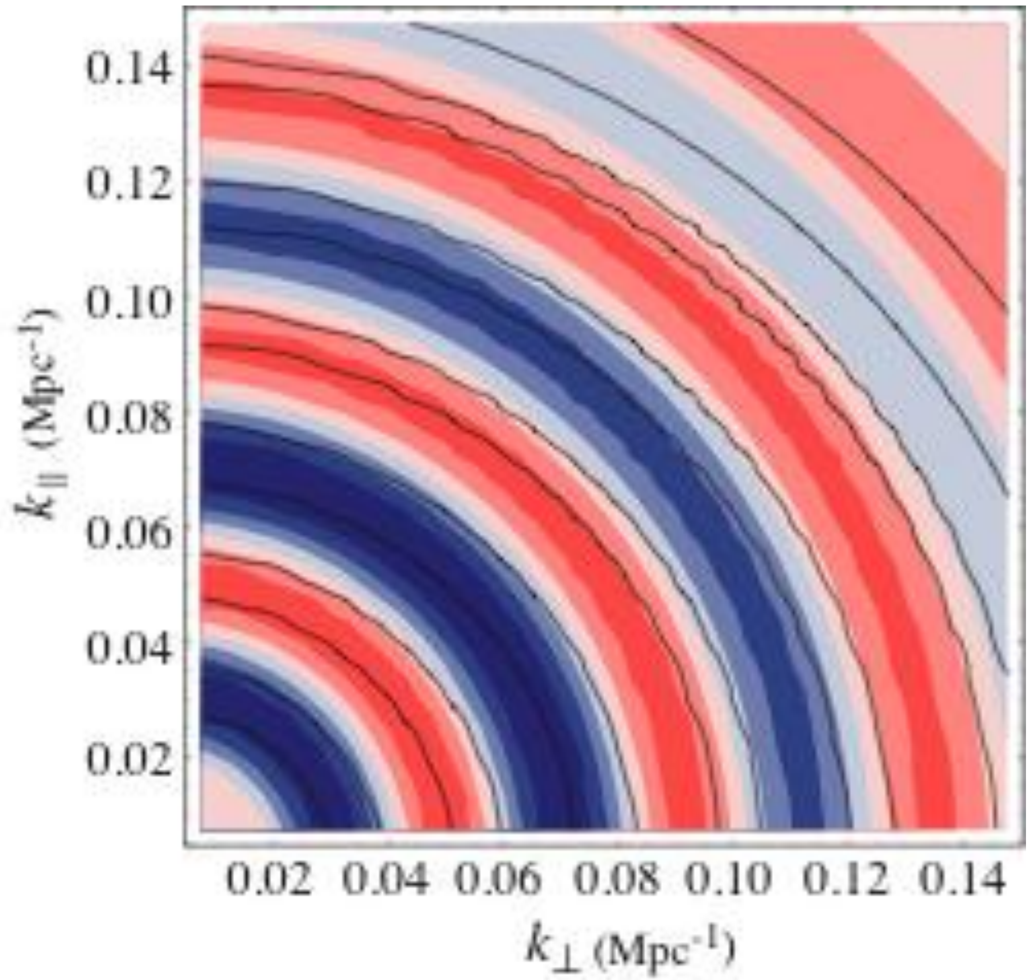
Changes in cosmological model alter measured BAO scale by:

Radial direction $$\frac{c}{H(z)}\Delta z$$

Angular direction

$$(1+z)D_A\Delta\theta$$

Gives rise to the "rings of power"



Hu & Haiman 2003, astro-ph/0306053

Baryon features as a standard ruler

Changes in cosmological model alter measured BAO scale by:

Radial direction

$$\frac{c}{H(z)}\Delta z$$

Angular direction

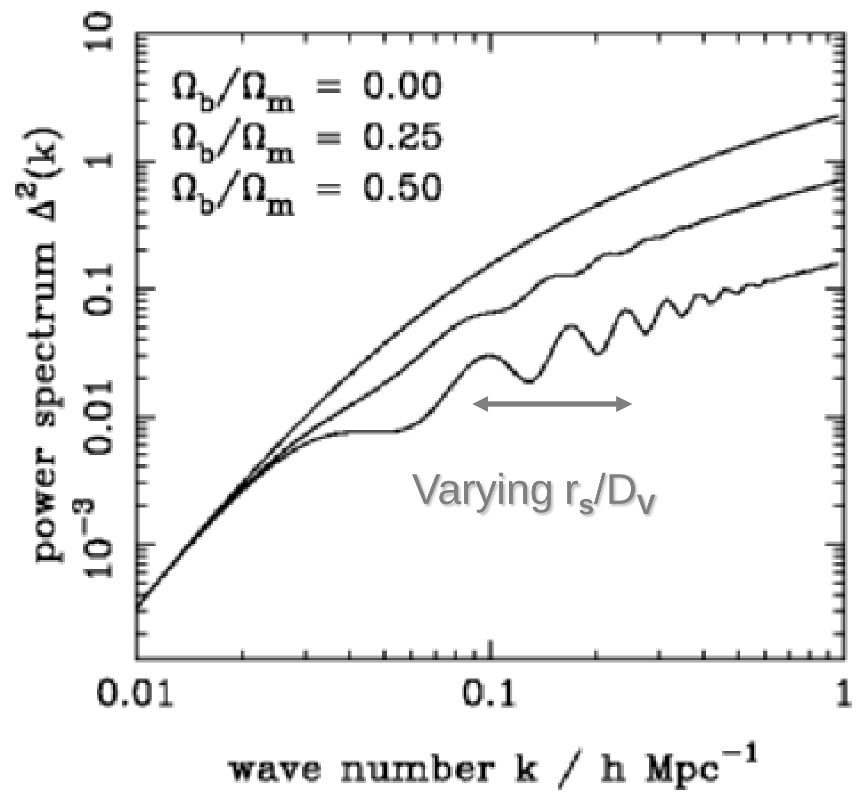
$$(1+z)D_A\Delta\theta$$

If we are considering radial and angular directions using randomly placed galaxy pairs, we constrain (to 1st order)

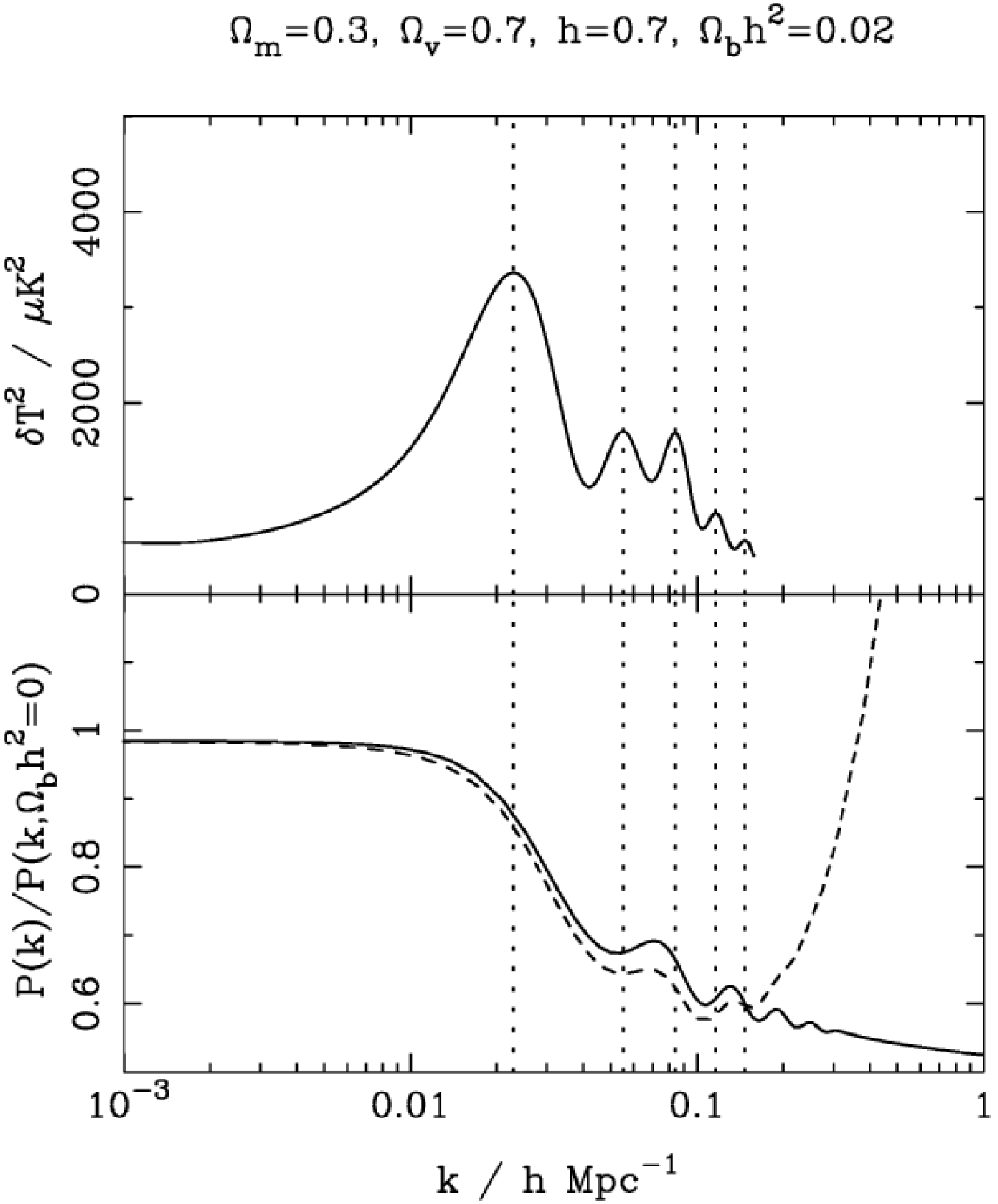
$$D_V = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

BAO position (in a redshift slice) therefore constrains some multiple of

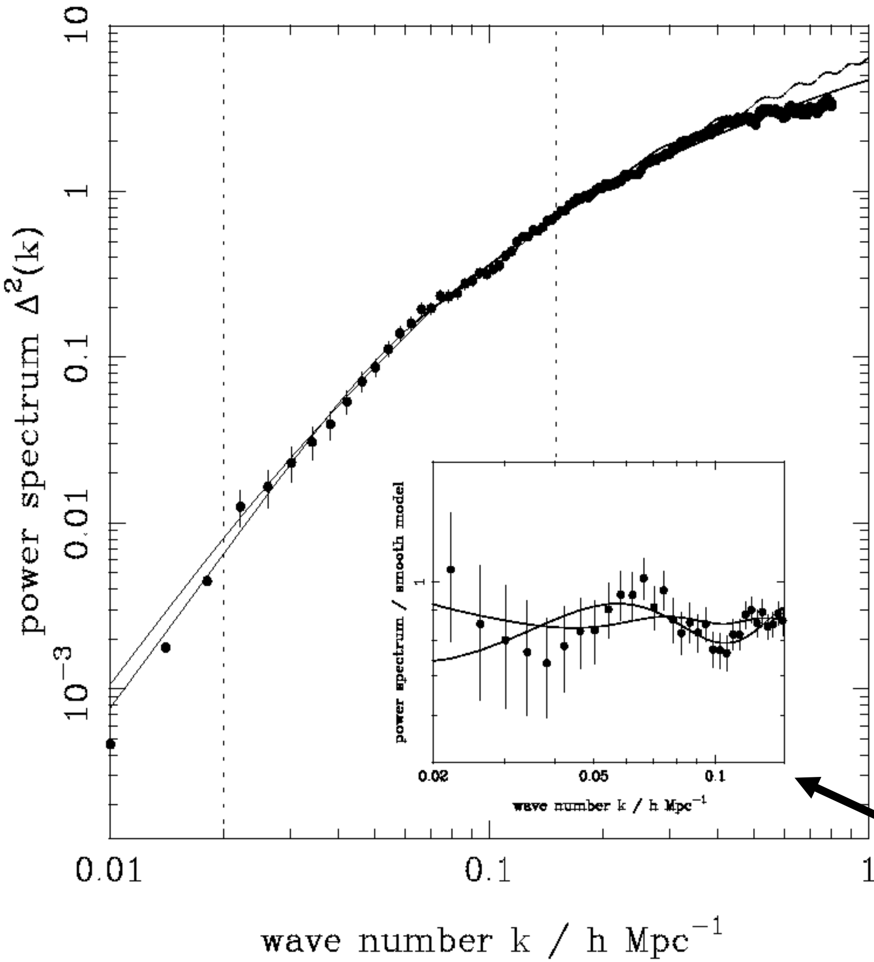
$$\frac{r_s}{D_V}$$

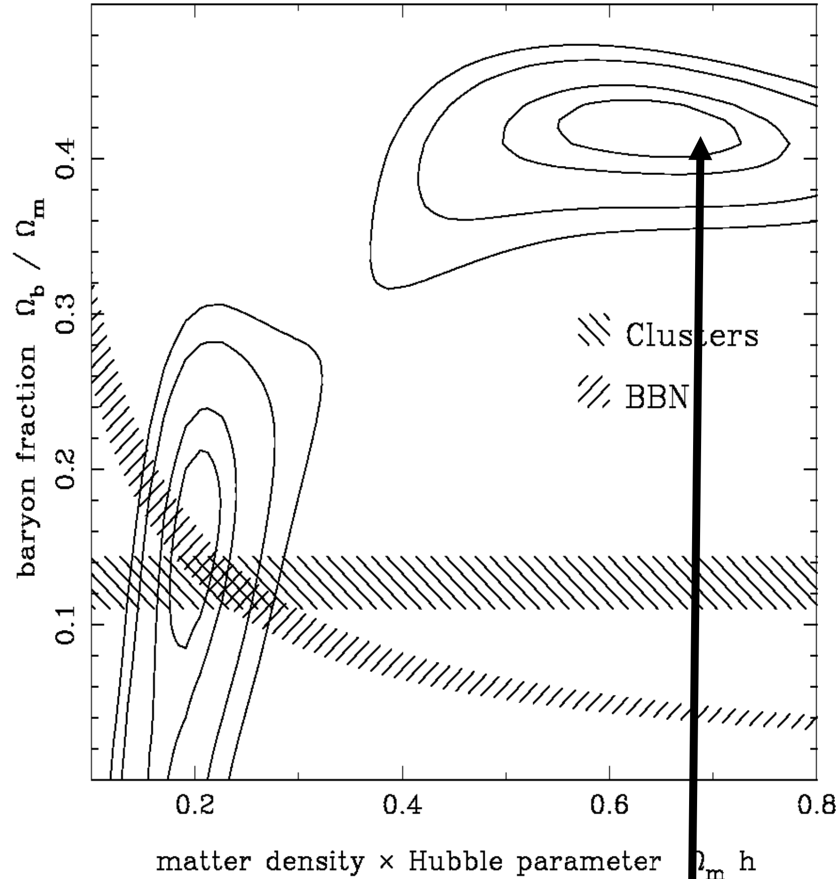


Relationship between CMB and matter power spectra



2dFGRS: the wiggles that weren't

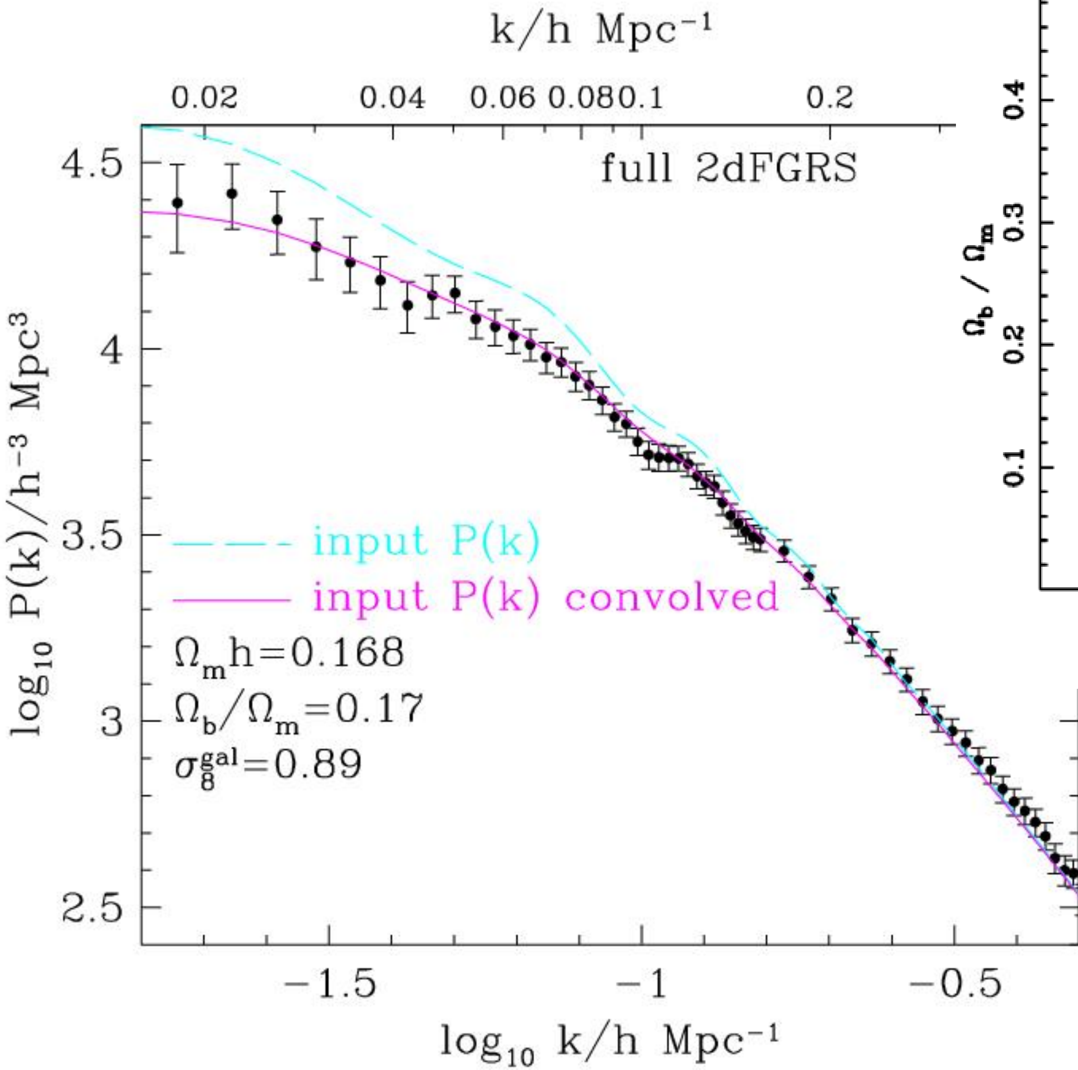


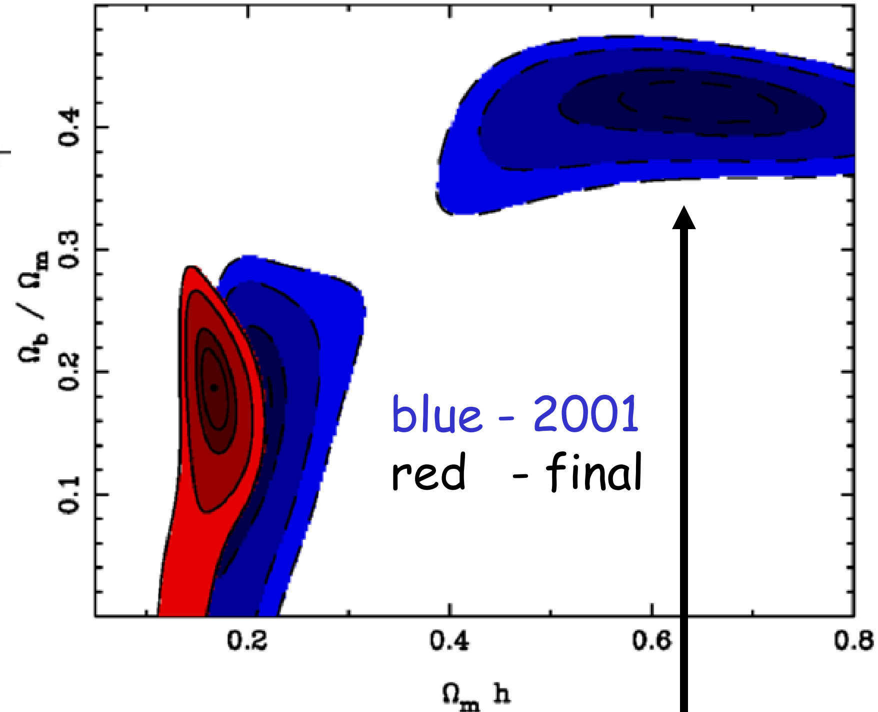


cosmological interpretation of wiggles requires high baryon fraction

Percival et al. 2001, MNRAS, 327, 1297

2dFGRS: the wiggles that were

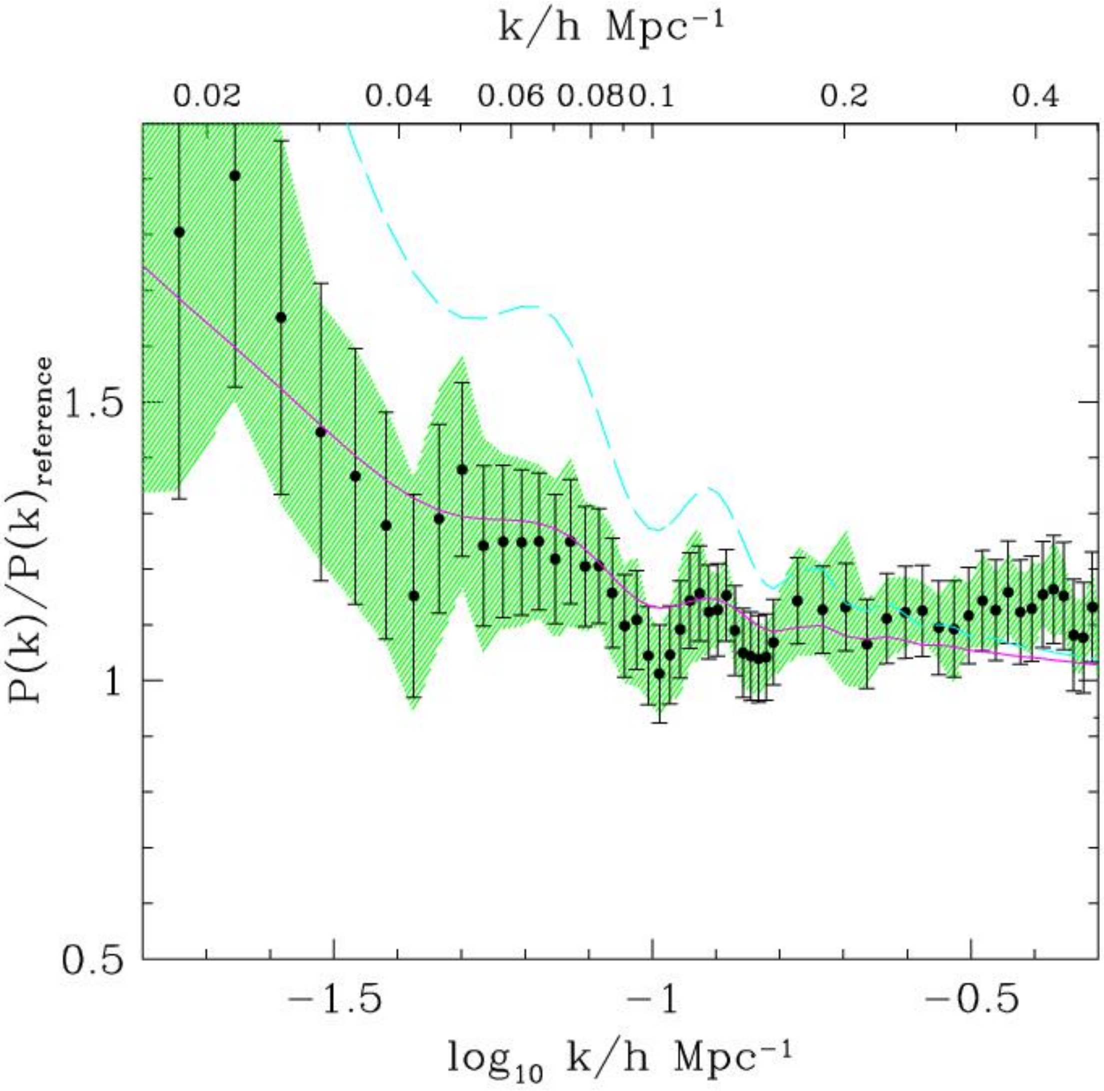




now only one solution
– high baryon solution
has disappeared

Cole, Percival et al. 2005, MNRAS, 362, 505

2dFGRS: the wiggles that were



CDM models fit the power spectrum adequately well with best fit parameters (assuming n_s=1, h=0.72)

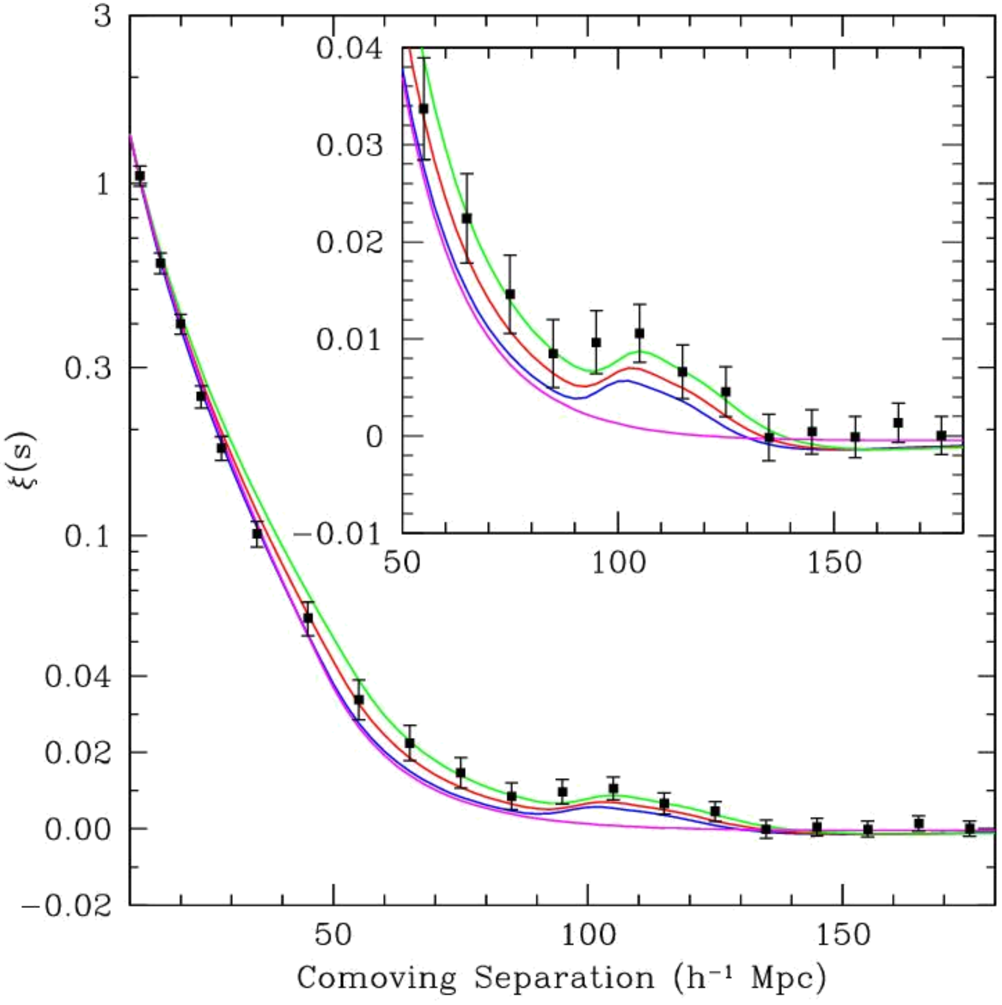
$\Omega_m h$ = 0.168±0.016
Ω_b/Ω_m= 0.185±0.046

Cole, Percival et al. 2005, MNRAS, 362, 505

SDSS LRG correlation function analysis

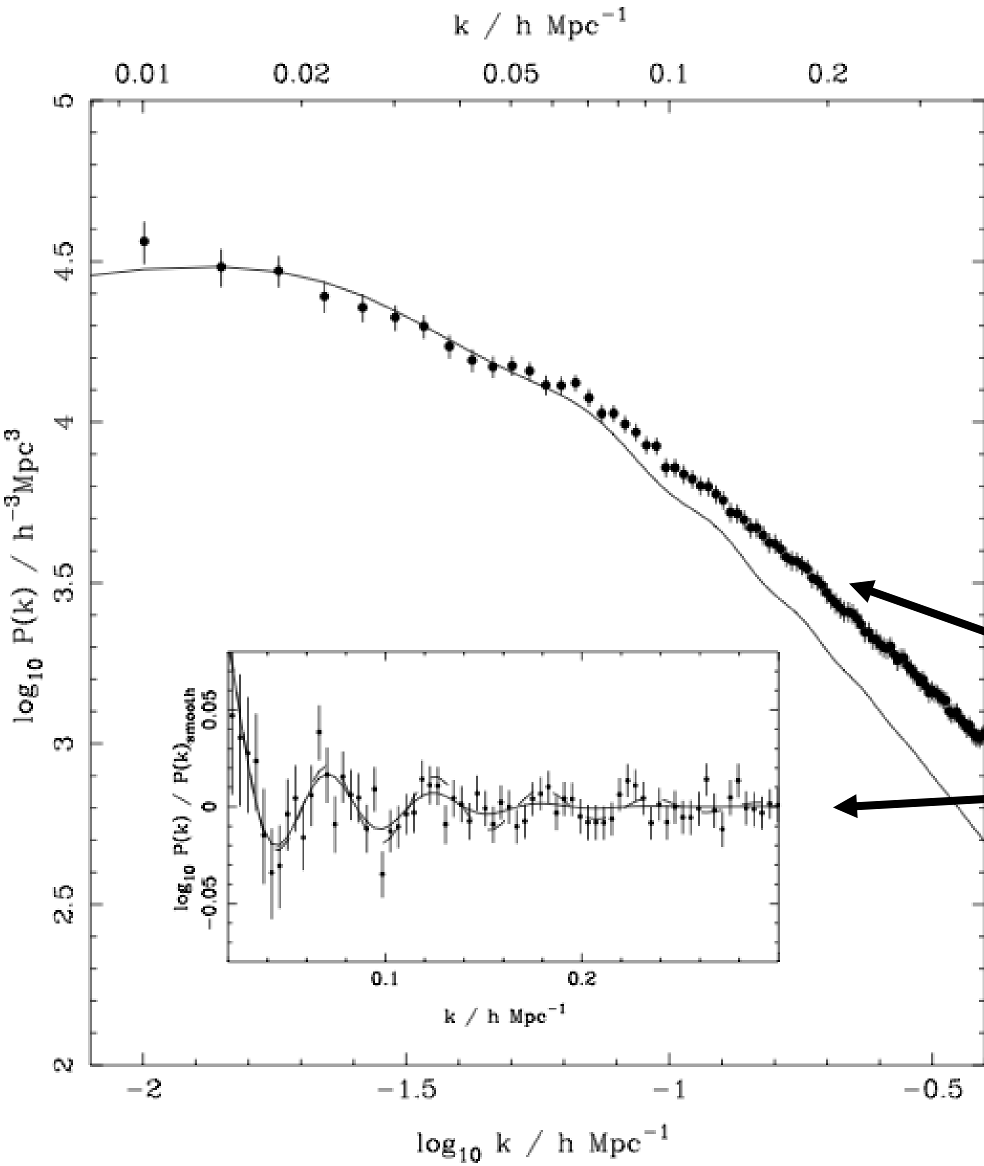
Again, CDM models fit the correlation function adequately well (although peak height is slightly too large) with (assuming n_s=1, h=0.72)

assuming $\Omega_b h^2$ =0.024,
$\Omega_m h^2$ =0.133±0.011,
Giving Ω_b/Ω_m= 0.18



Eisenstein et al., 2005, ApJ, 633, 560

BAO in the SDSS DR5 (combined main galaxies + LRGs)



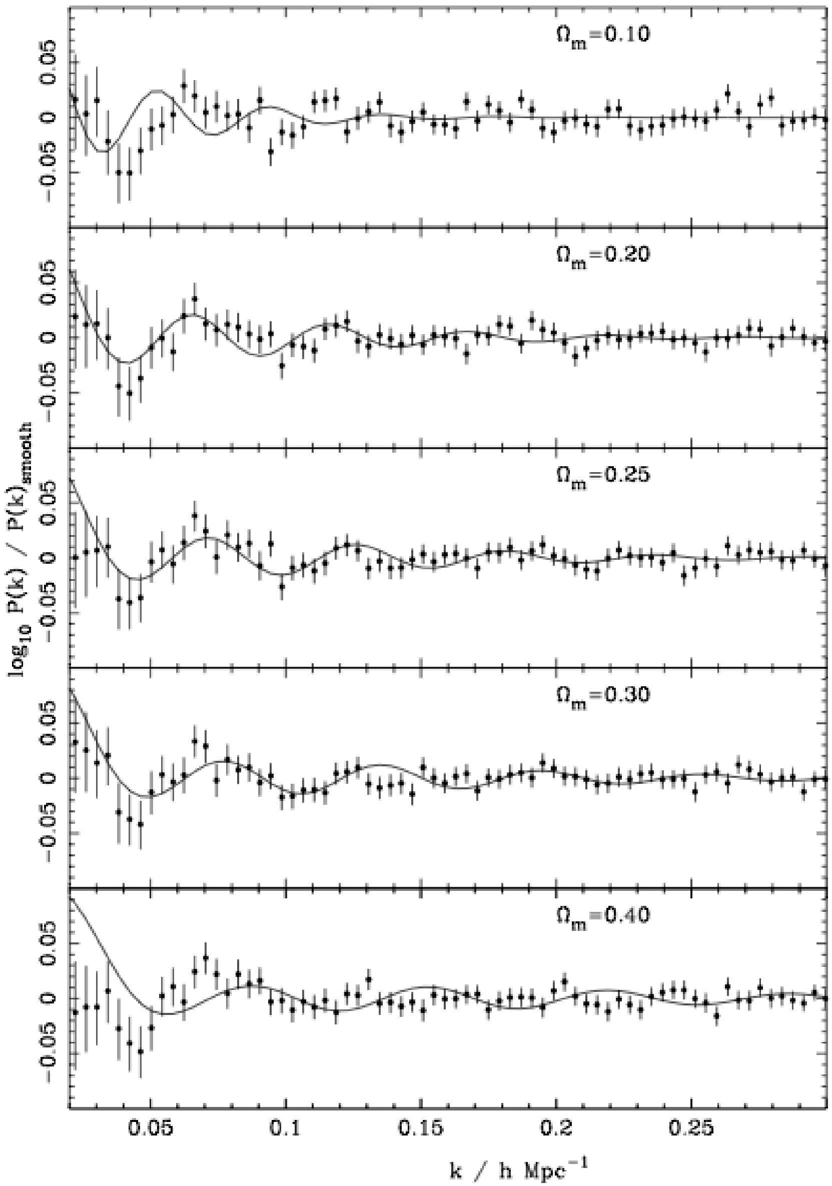
Compared with WMAP 3-year best fit linear CDM cosmological model.
N.B. not a fit to the data, but a **prediction** from WMAP.

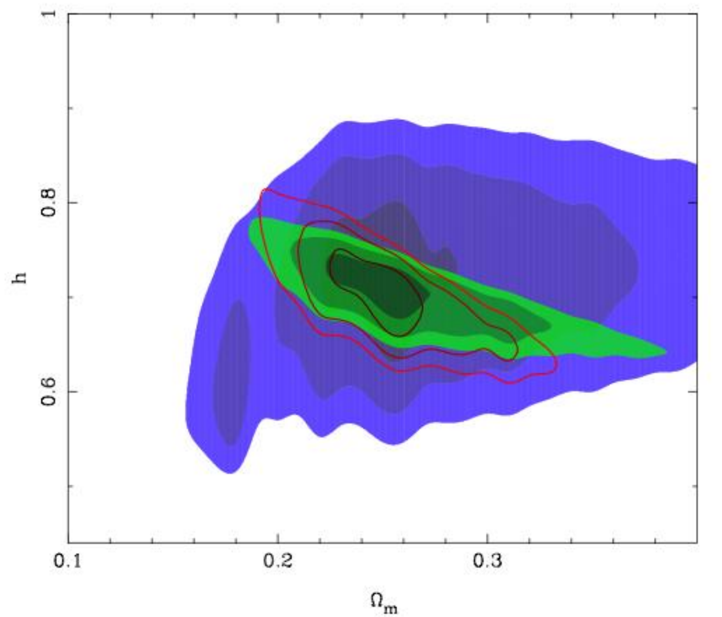
Interesting features:

1. Overall P(k) shape
2. Observed baryon acoustic oscillations (BAO)

Percival et al., 2007, ApJ, 657, 645

Matter density from combined SDSS DR5 BAO



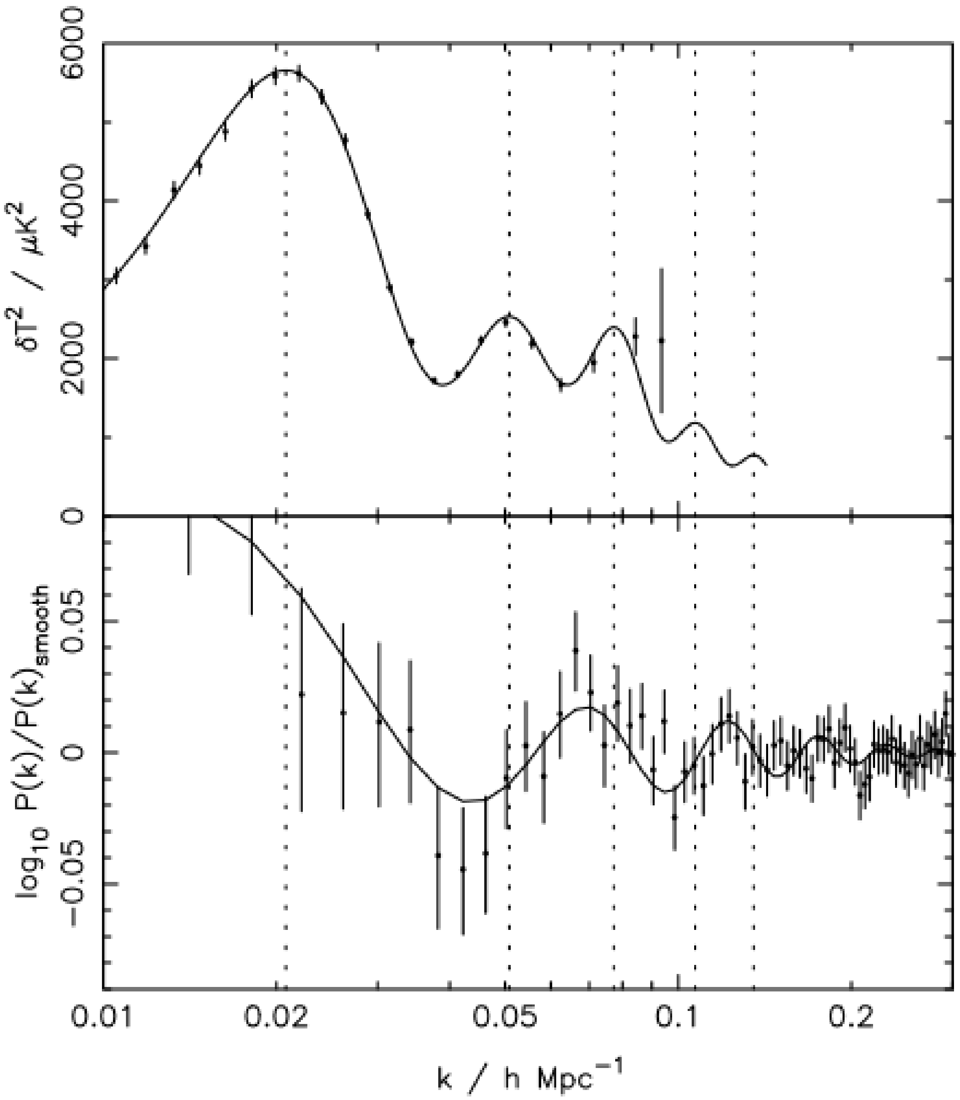


When combined with, and marginalised over the WMAP 3-year peak position, For flat ΛCDM cosmologies

$$\Omega_M = 0.257^{+0.029}_{-0.024}$$

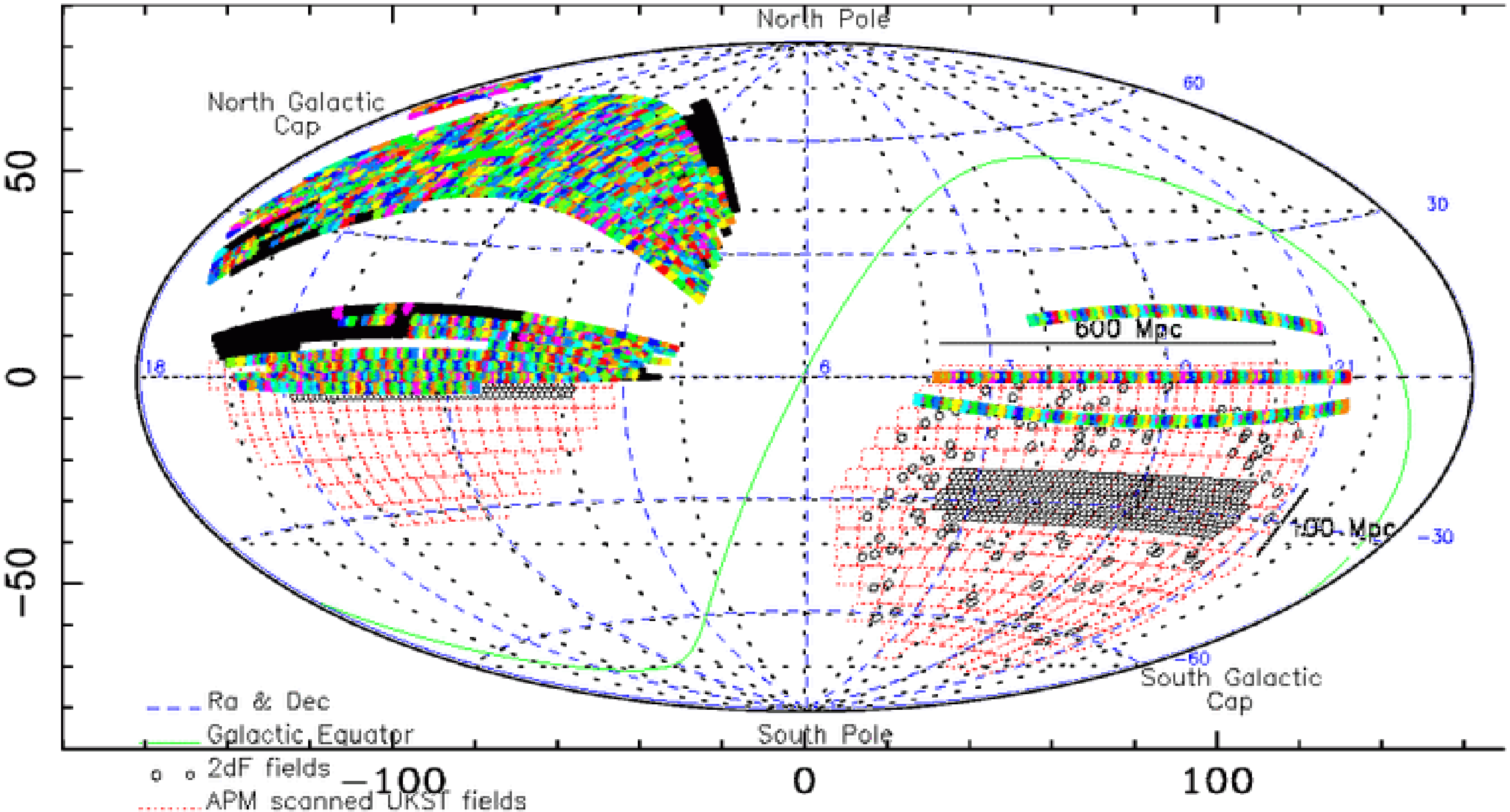
Percival et al., 2007, ApJ, 657, 51

Comparison between LSS and CMB BAO



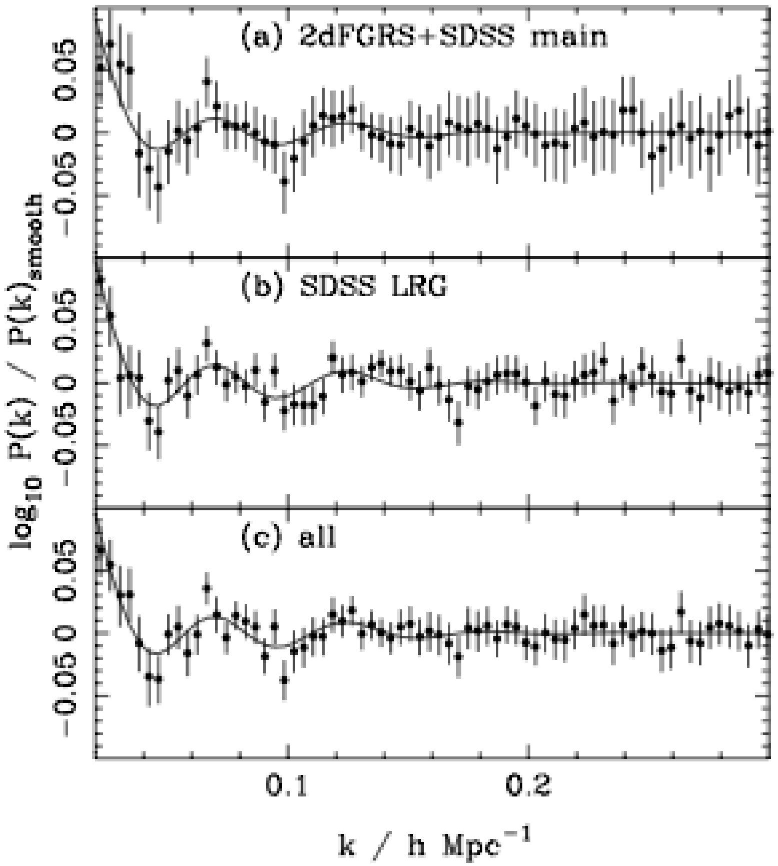
Shows potential for measuring the geometry of the universe, either from CMB--LSS comparison, or comparing different redshifts in LSS surveys.

Combining the SDSS and 2dFGRS surveys



Work in collaboration with: Shaun Cole, Dan Eisenstein, Bob Nichol, John Peacock, Adrian Pope, Alex Szalay (should arrive on astro-ph soon)

BAO in galaxy samples drawn from the SDSS & 2dFGRS

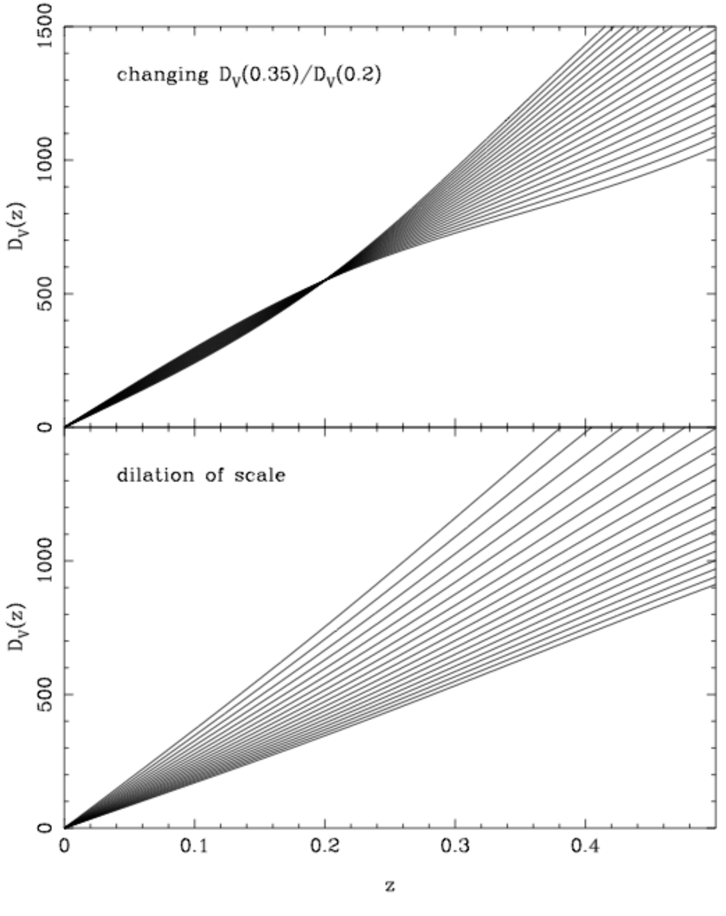


BAO detected at low redshift
0<z<0.3 (effective redshift 0.2)

BAO detected at high redshift
0.15<z<0.5 (effective redshift 0.35)

BAO from combined sample
(detected over the whole
redshift range 0<z<0.5)

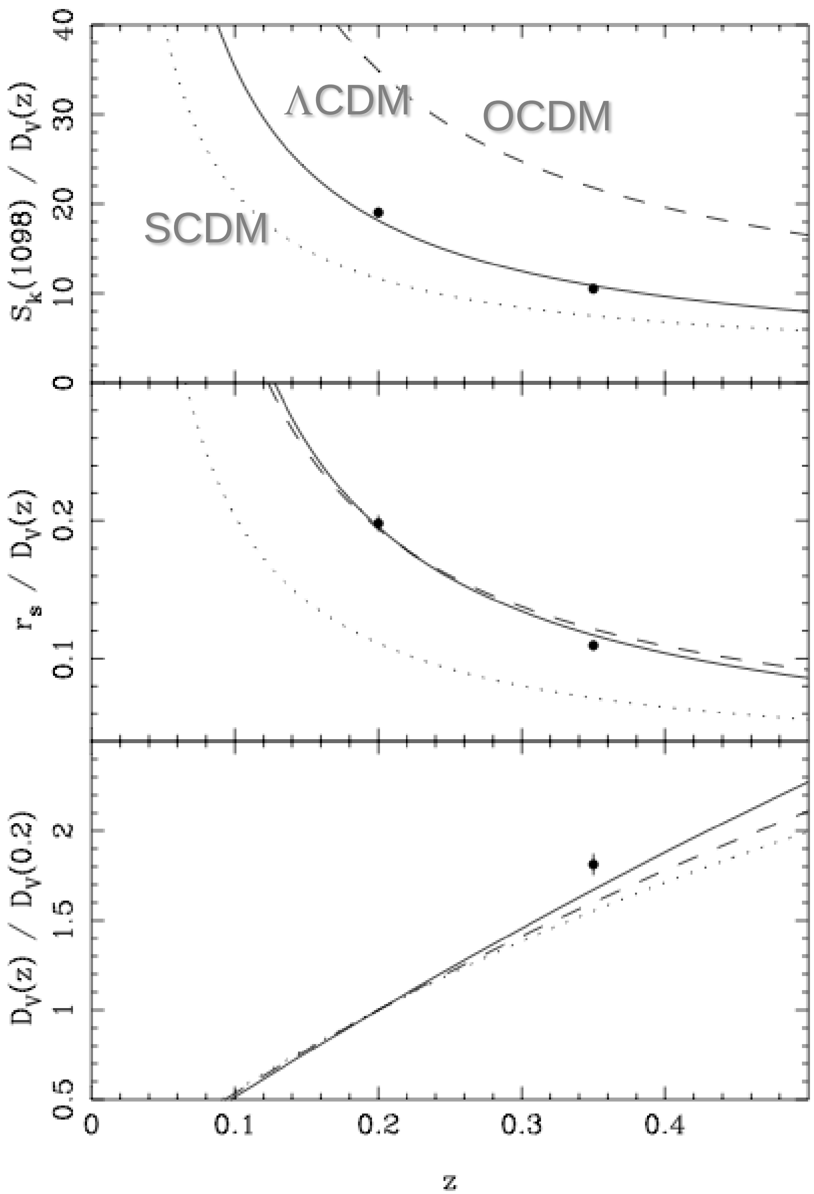
Problem: need to know cosmology before we find BAO



- Galaxy redshifts need to be converted to distances before BAO can be measured
- Not a problem for small sets of models (1-2 parameters), but time consuming for more
- Solve problem by parametrising distance-redshift relation by smooth fit: can then be used to constrain multiple sets of models
- For SDSS+2dFGRS analysis, choose two modes at z=0.2 and z=0.35, for fit to D_V

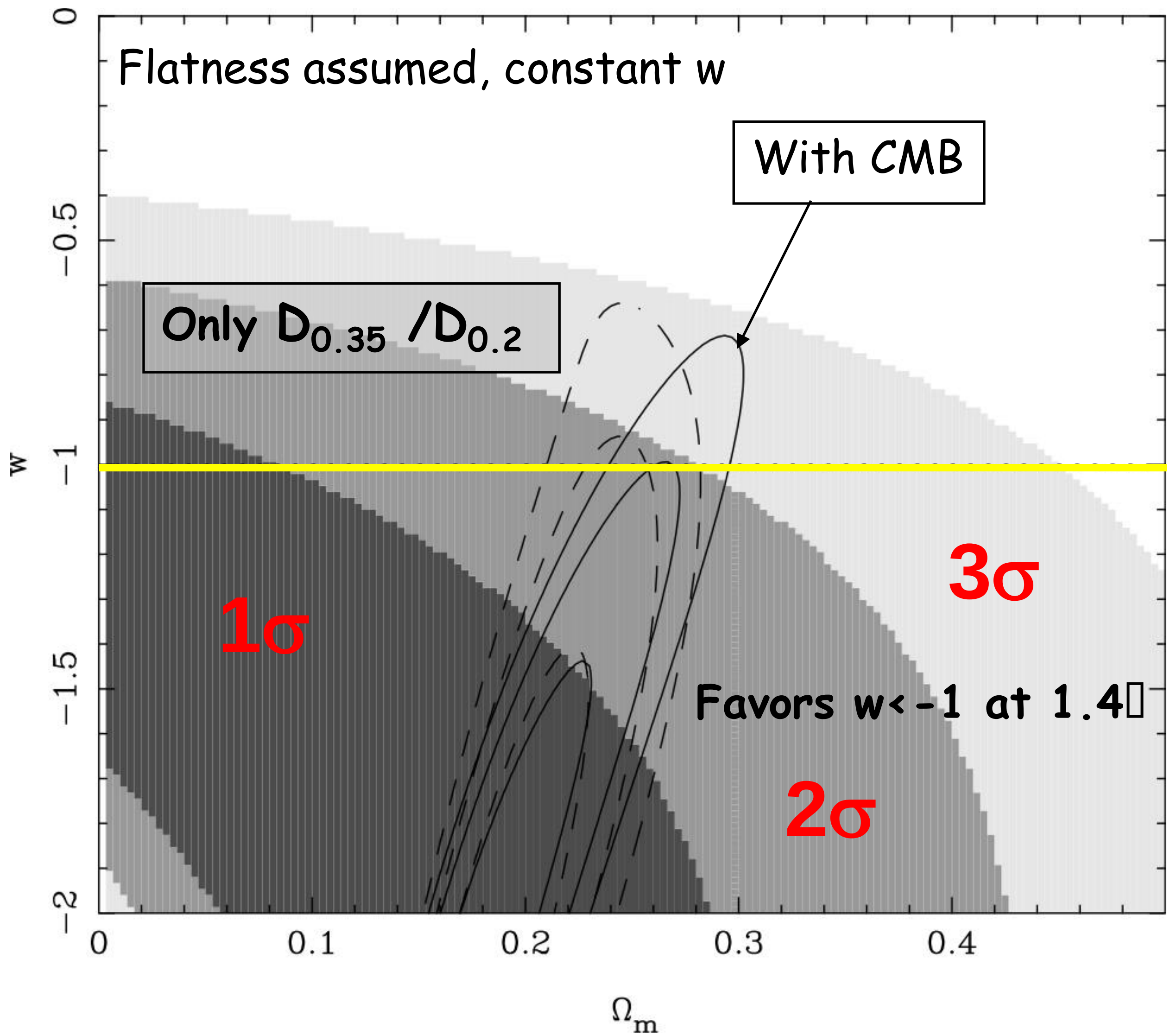
$$D_V(z) = \left[D_A(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$

BAO distance constraints

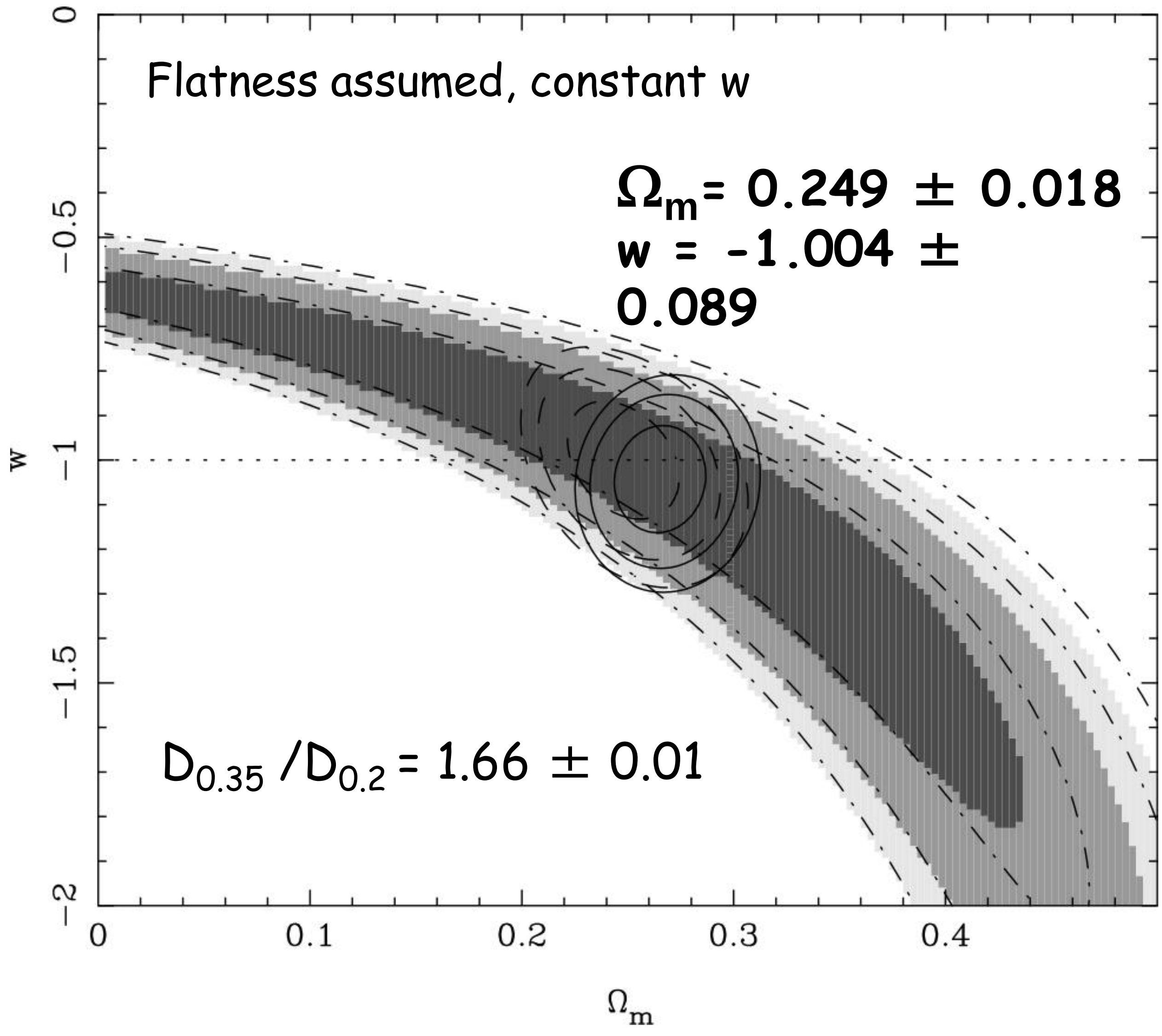


- Constraint including observed peak distance constrain from CMB $r_s/d_A(\text{cmb})=0.0104$
- Constraint fitting $r_s/D_V(z)$
- Constraint from $D_V(0.35)/D_V(0.2)$

Cosmological constraints



Cosmological constraints



Future dark energy surveys

Dark Energy Task Force (DETF)

DETF Terminology

- Stage II are experiments going on now (most are still limited by statistics and systematics)
    - e.g. SNLS, WiggleZ, SDSS-II Supernovae Survey, AS2
- Stage III are next generation (before end of decade). Investigate systematics and gain factor of >3
    - e.g. DES, Pan-STARRS, WFMOS
- Stage IV are next decade and gain factor of 10
    - e.g. SKA, DUNE, JDEM (SNAP)

Albrecht et al, DETF report,
astro-ph/0609591
Trotta & Bower, A&G review, astro-ph/0607066

Will future surveys be able to measure BAO?

Standard formula for power spectrum error (from spectroscopic survey) is given by

$$\sigma_{ln\,P} = \frac{2\pi}{(Vk^2\Delta k)^{1/2}}\left(\frac{1+nP}{nP}\right)$$

photometric redshifts (of width d/h^{-1}Mpc), radial power spectrum is damped by

$$\exp[-(2\pi kd)^2]$$

Spheric… er spectrum is damped by

$$\frac{\sqrt{\pi}\mathrm{erf}(kd)}{2kd}$$

Current SDSS BAO (benchmark for cosmological constraints) have

- For z=0.2 SDSS main galaxies and 2dFGRS galaxies

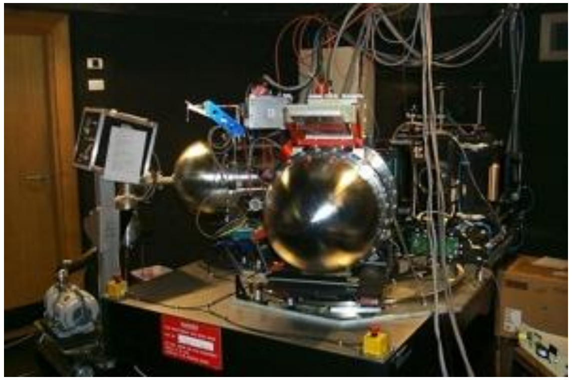
$$\sigma_{\ln P} = 0.17$$

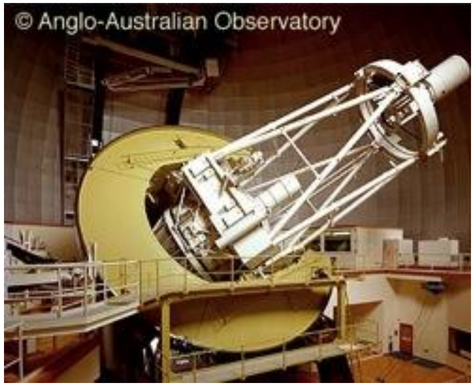
- For z=0.35 SDSS LRGs

For $\Delta\sigma_{\ln P} = 0.10$

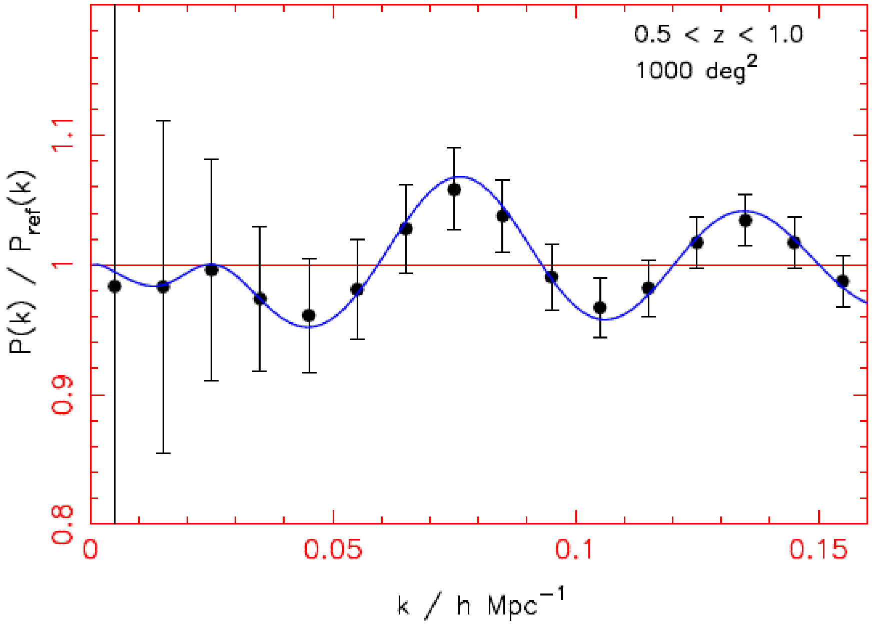
(empirically determined)

Wiggle-Z





- Measure distance to ~2% at z=0.75
- 1000 deg^2 with 400000 emission line galaxies 0.5<z<1.0
- Awarded 220 AAT nights
- Ongoing (2006 - 2009)

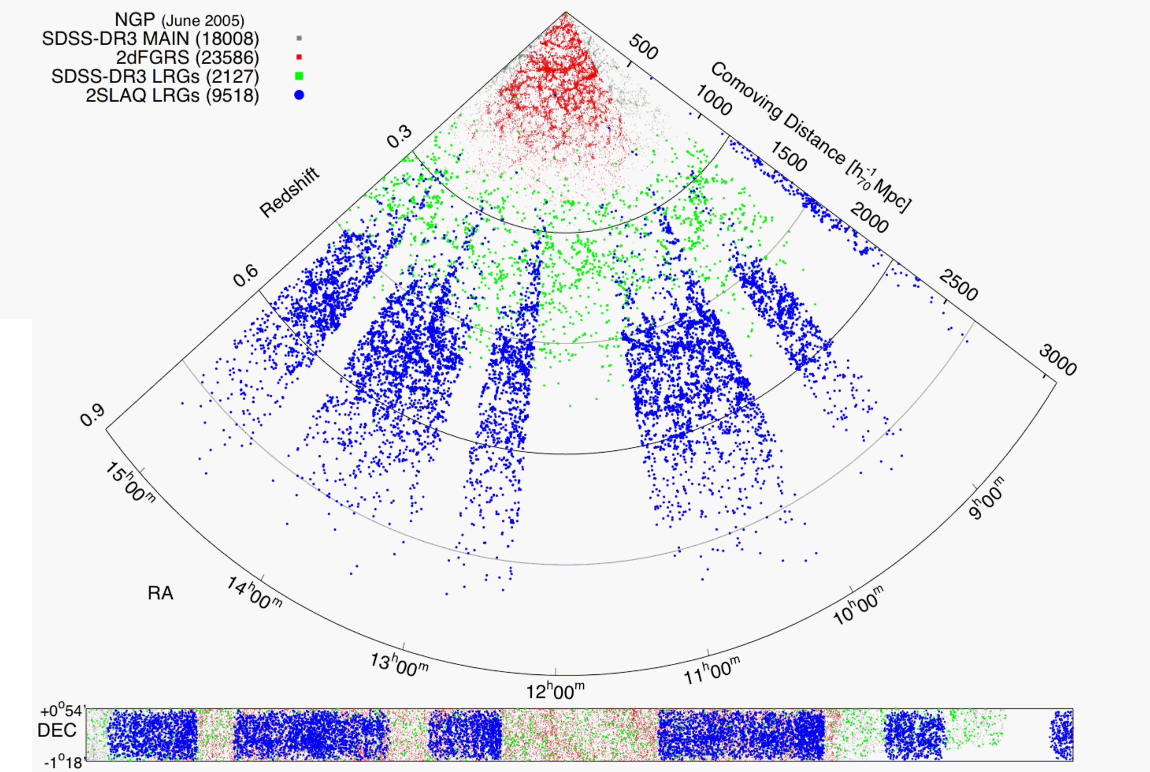


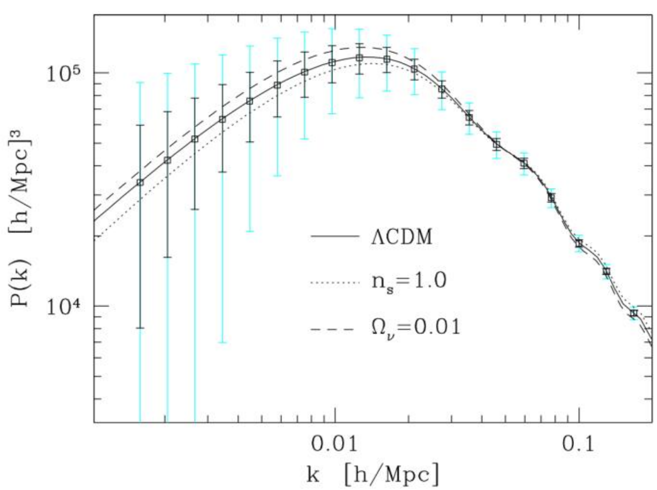
After SDSS-II (AS2)

Baryon Oscillation Spectroscopic Survey (BOSS)

- Measure distance to ~1% at z=0.35 and z=0.6
- 10000 deg^2 with 1.5m LRGs to 0.2<z<0.8
- 160k quasars at 2.3<z<2.8
- Starting 2009
- h to 1% with SDSS SNe

2SLAQ (www.2slaq.info)





Dark Energy Survey (DES)

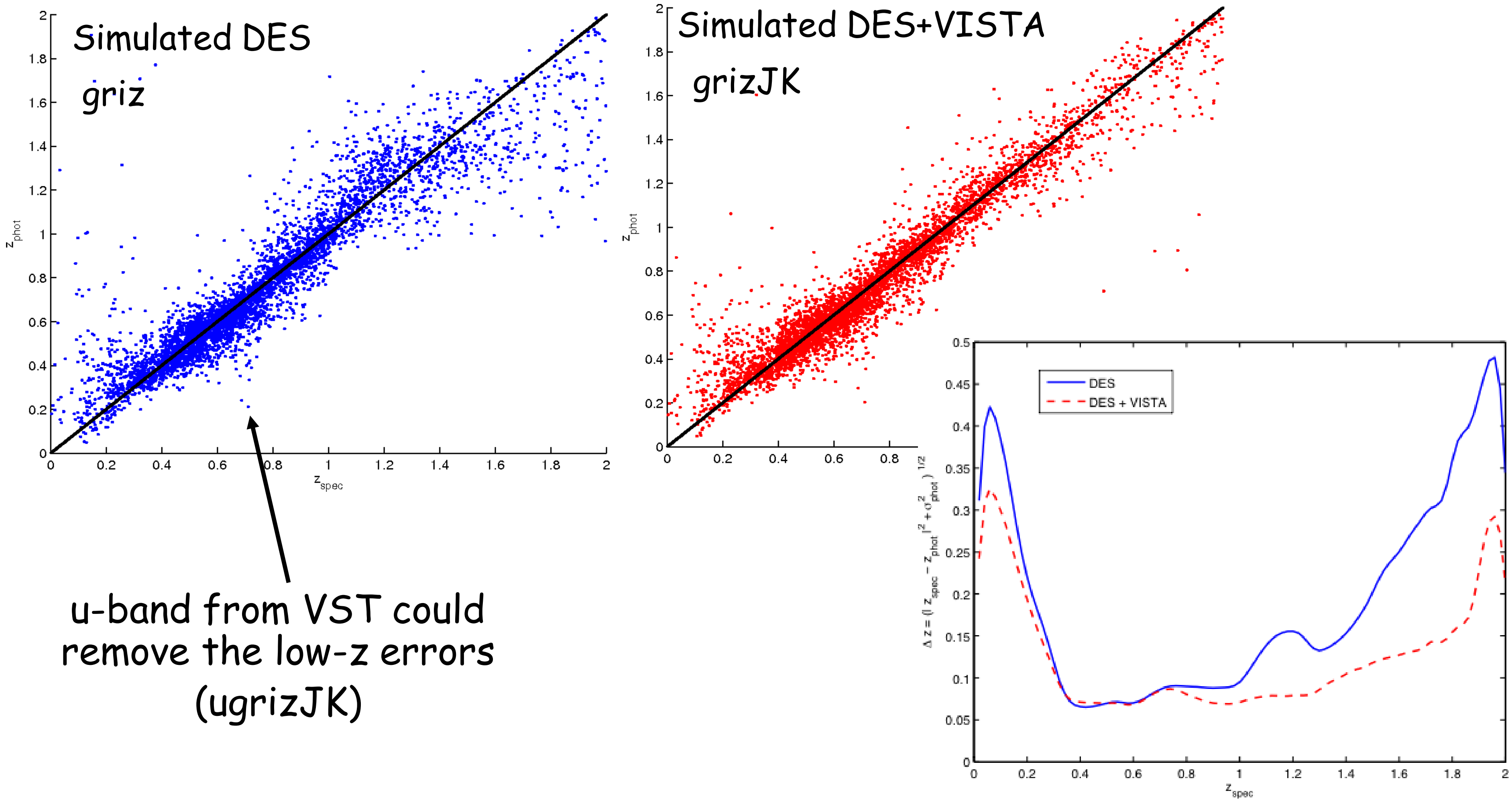
- 5000 sq deg multiband (g,r,i,z) survey of SGP using CTIO Blanco with a new wide-field camera
- 9 sq deg time domain search for SNe

Method	$\sigma(\Omega_{DE})$	$\sigma(w_0)$	$\sigma(w_a)$	z_p	$\sigma(w_p)$	$[\sigma(w_a)\sigma(w_p)]^{-1}$
BAO	0.010	0.097	0.408	0.29	0.034	72.8
Clusters	0.006	0.083	0.287	0.38	0.023	152.4
Weak Lensing	0.007	0.077	0.252	0.40	0.025	155.8
Supernovae	0.008	0.094	0.401	0.29	0.023	107.5
Combined DES	0.004	0.061	0.217	0.37	0.018	263.7
DETF Stage II Combined	0.012	0.112	0.498	0.27	0.035	57.9

Table 1: 68% CL marginalized forecast errorbars for the 4 DES probes on the dark energy density and equation of state parameters, in each case including Planck priors *and* the DETF Stage II constraints. The last column is the DETF FoM; z_p is the pivot redshift. Stage II constraints used here agree with those in the DETF report to better than 10%.

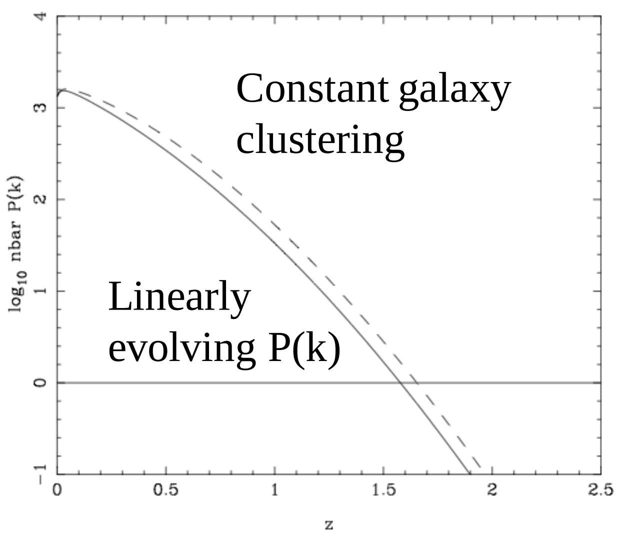
DES Photo-z's

DES science relies on good photometric estimates of the 300 million expected galaxies

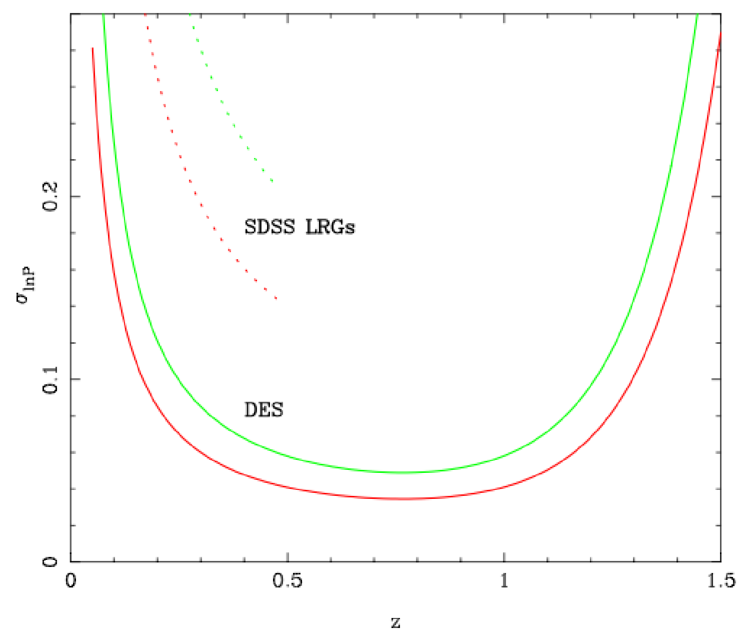


ANNz: Collister & Lahav 2005, Abdalla et al.

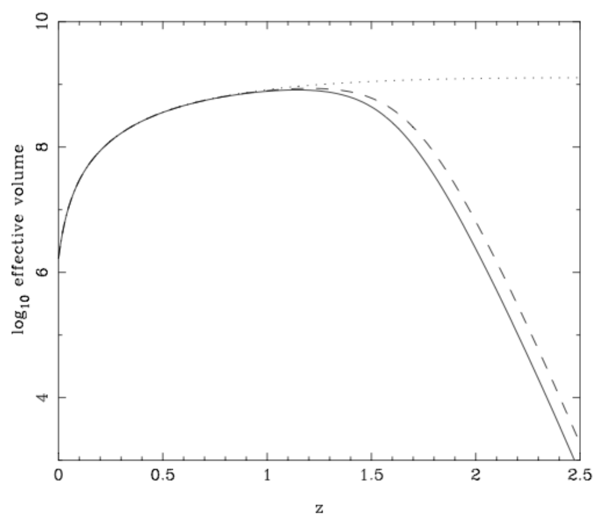
Shot noise vs. cosmic variance for DES



Nbar P(k) for 3D analysis of survey



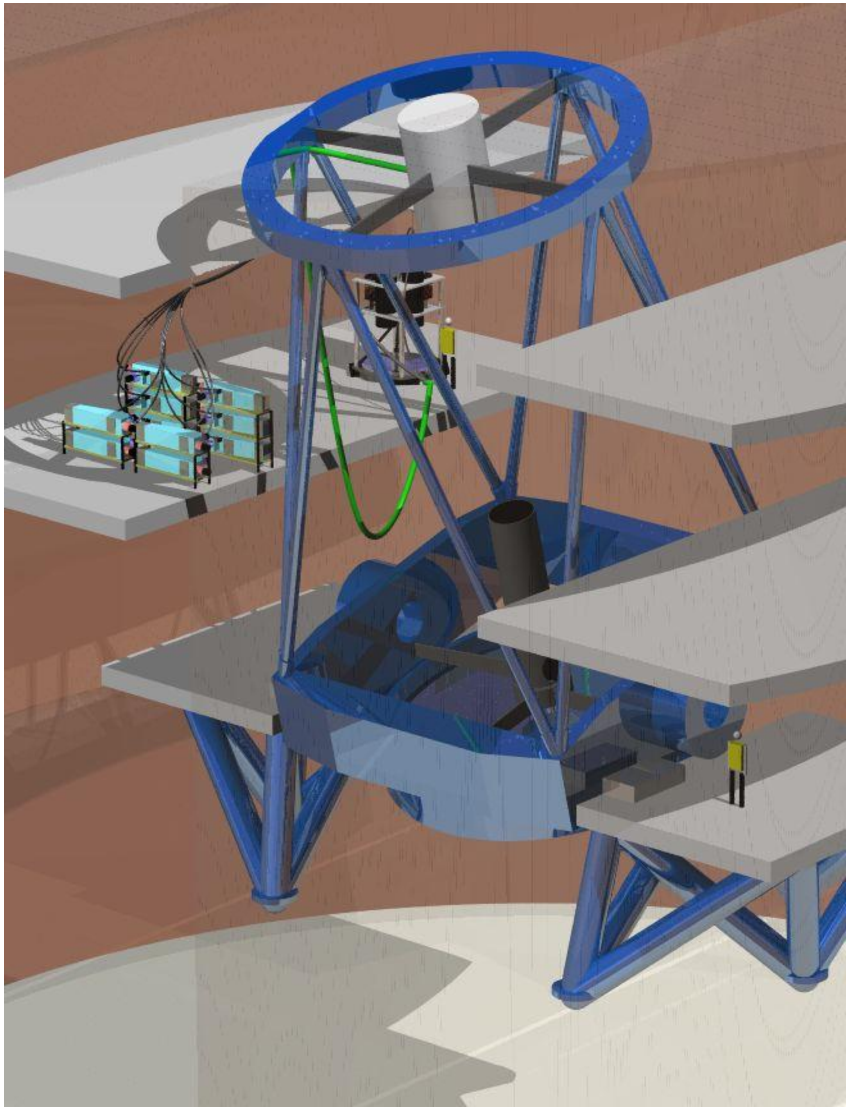
Change in effective volume for LSS analyses in DES in shells of width Δz=0.05



Predicted $\sigma_{\mathbf{lnP}}$ for DES as a function of redshift, for Δz=0.1 and Δz=0.05 (assumes photo-z error of $\sigma_{\mathbf{d}}$=150h^{-1}Mpc)

The WFMOS concept

- Proposed MOS on Subaru via an international collaboration of Gemini and Japanese astronomers
- 1.5deg FOV with 4500 fibres feeding 10 low-res spectrographs and 1 high-res spectrograph
- ~20000 spectra a night *(2dfGRS at z~1 in 10 nights)*
- DE science, Galactic archeology, galaxy formation studies and lots of ancillary science from database
- Design studies underway; on-sky by 2013
- Next Generation VLT instruments; meetings in Garching
- Combine with an imager and do “SDSS at z=1”
- If BOSS goes ahead, best strategy would be to concentrate on high redshifts



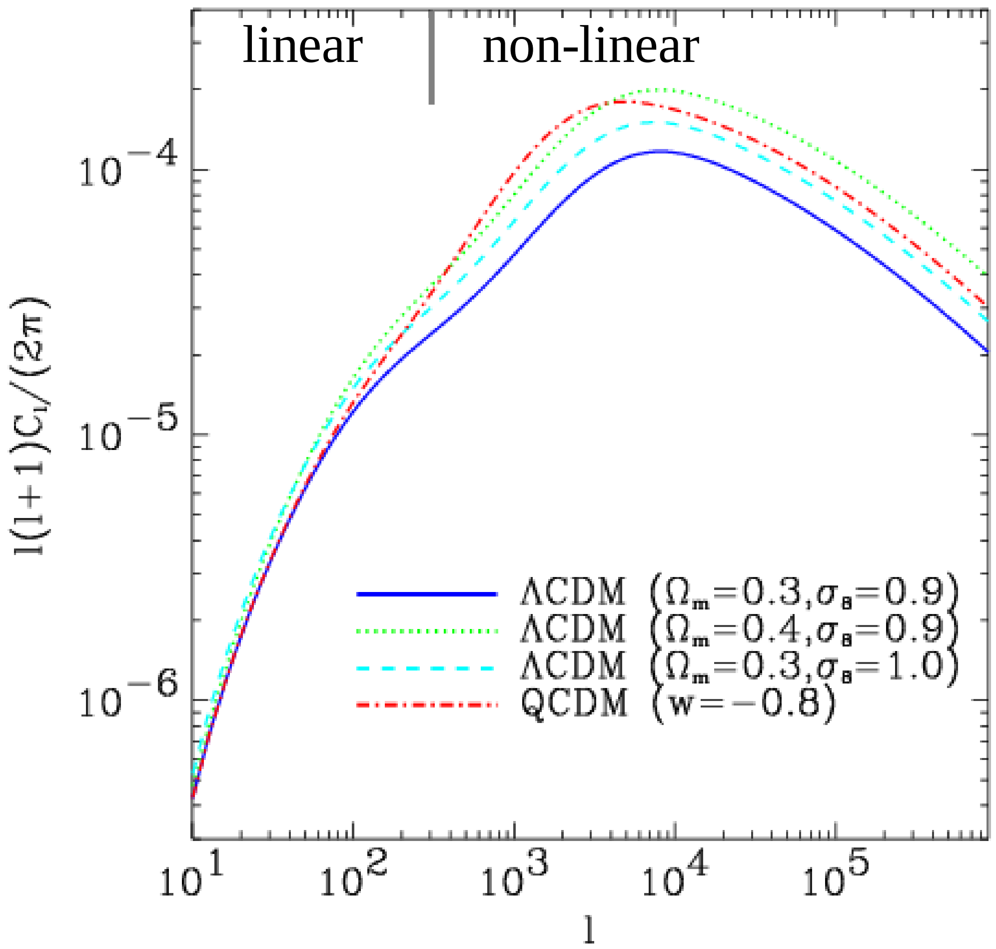
The WFMOS legacy (facility instrument)

z range	R limit (AB)	Volume (h^{-1} Gpc)	Area (sq degs)	Number	Nights
0.5 - 1.3	***22.7***	***4***	***2000***	***2000000***	***100***
2.3 - 3.3	***24.5***	***1***	***300***	***600000***	***100***
Galaxy Archeology				***400000***	***400***

(Glazebrook et al. 2005)

- *Galaxy Evolution:* Every galaxy in Coma ($M_r < -11$)
- *IGM and Quasars:* Simultaneously observing QSOs and galaxies in the same fields
- *Calibrate photo-z's:* LSST and DES require > a few 10^5 unbiased redshifts (Abdalla et al. 2007)

Alternative approaches: weak lensing



Expected lensing power spectrum in different cosmological models (Refregier review)

Given degeneracies between w, Ω_M, σ_8 and Γ, weak lensing is primarily sensitive only to the linear growth rate of fluctuations

Alternative approaches: ISW effect

The ISW probes the fluctuations on very large scales, where even quintessence predicts clustering of dark energy. The dark energy sound horizon divides smooth and clustered regimes; quintessence type models have large sound speeds (cs ~ 1) and the transition occurs near the horizon scale, but it can be smaller.

If the sound speed is large, the ISW effect is one of the few ways we can see its affects.

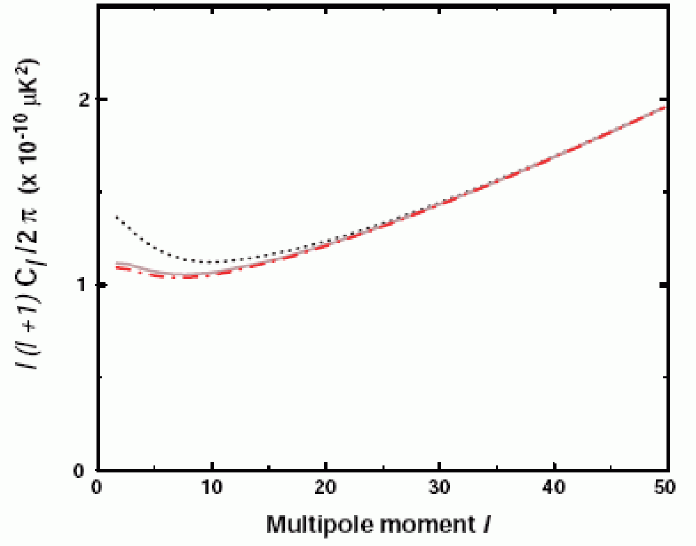
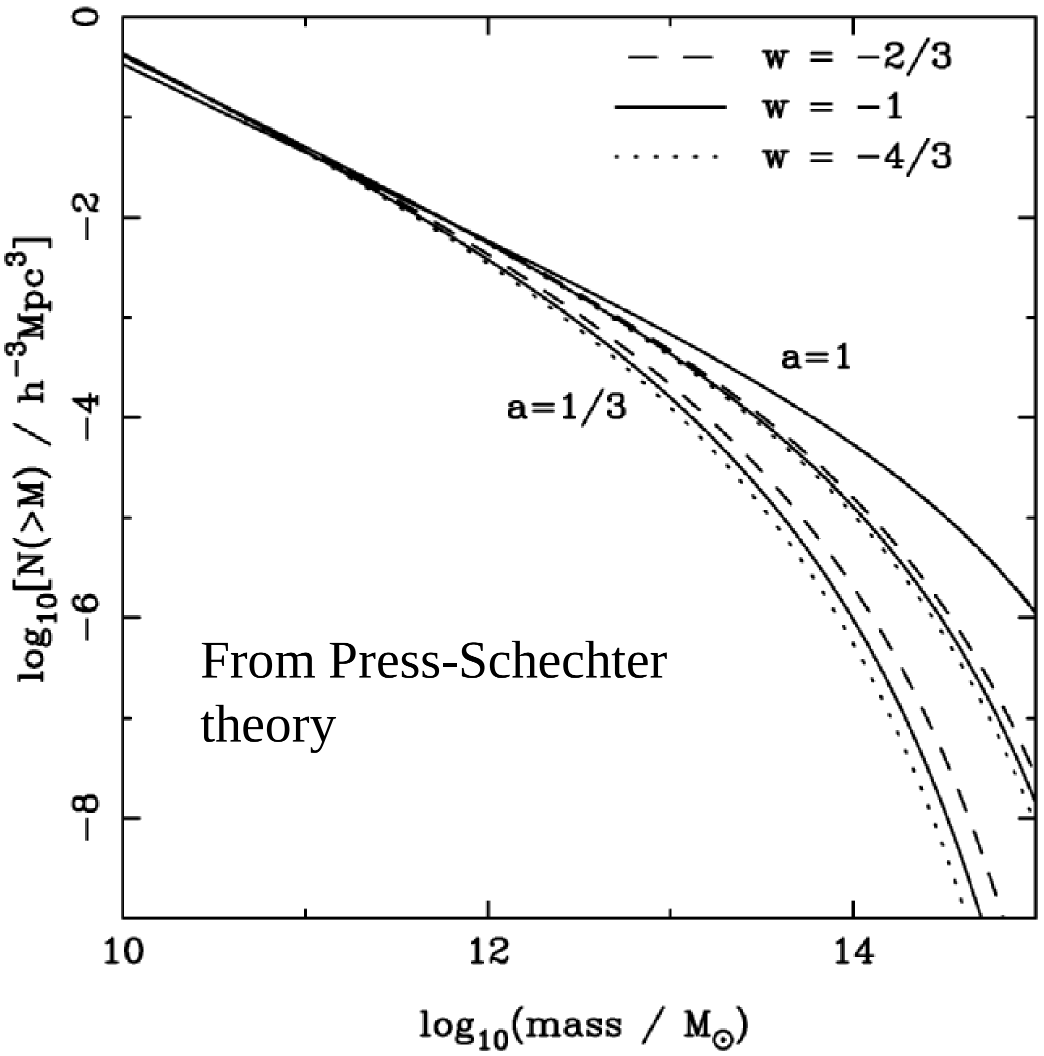


FIG. 2: Comparison of the lowest multipole moments of the CMB temperature power spectrum for a series of models with $w = -0.8$: (a) $c_s = 1$ (dotted); (b) $c_s = 1$ until $z = 5$ and then $c_s = 0$ for $z < 5$ (solid); and (c) $c_s = 0$ for all z (dot-dashed).

DeDeo, Caldwell & Steinhardt
astro-ph/0301284

low sound speed at low redshift would suppress ISW effect – not currently testable – possibly by LSST (Hu & Scranton astro-ph/0408456)

Alternative approaches: cluster counts

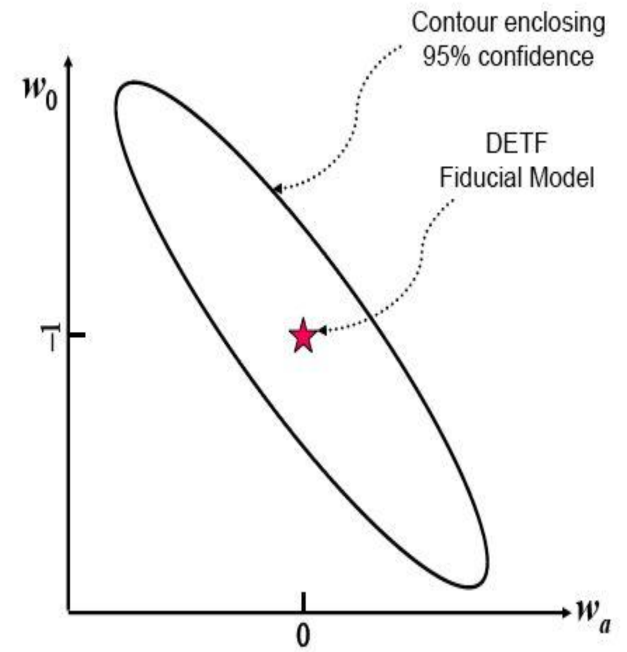


From Press-Schechter theory

- determination of observed masses – use of virial theorem needs further tests
- need to know mass function accurately using numerical simulations
  - Sheth & Tormen (1999)
  - Jenkins et al. (2001)
  - Warren et al. (2005)
- work progresses for DE models
  - Linder & White (2005)
- scatter in measured masses can affect observations
  - Lima & Hu (2005)

Figure of Merit

- Constraining equation of state, w, and its evolution in time is seen as the primary goal.
- The DE Task force created a Figure of Merit to compare different surveys and approaches
- It is the inverse of the 95% confidence contour in the w_0, w_a plane



$$
\begin{aligned}
w(z) &= w_0 + (1-a)w_a \\
&= w_p + w_a(a_p - a)
\end{aligned}
$$

a_p is the scale factor where w_p and w_a become independent

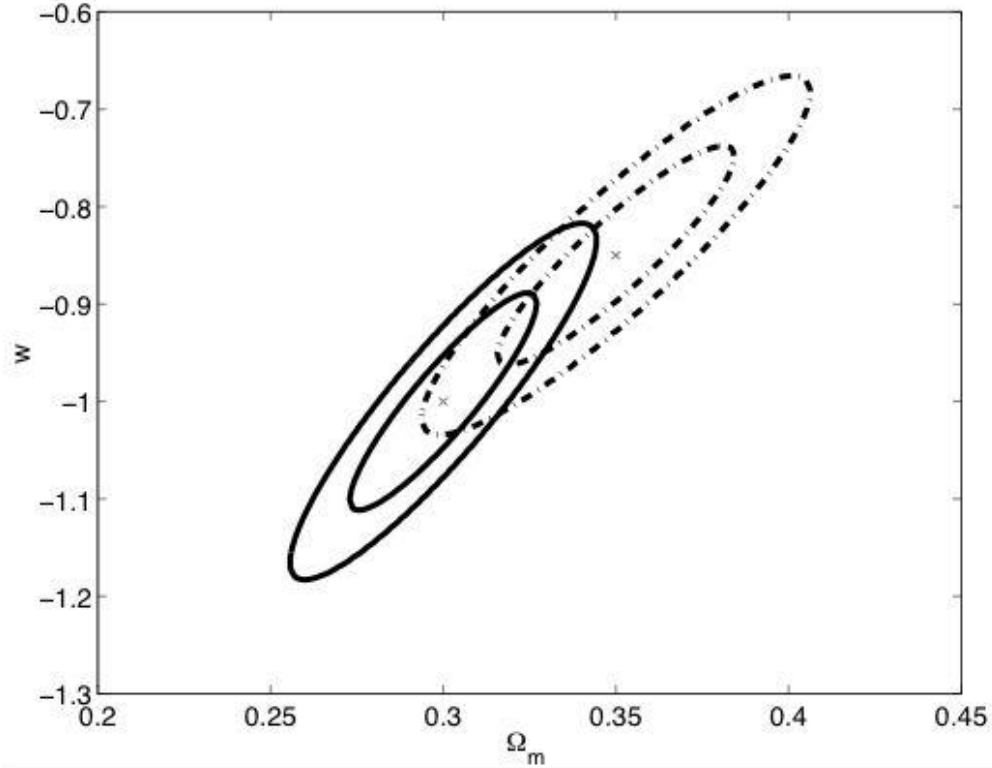
The DETF figure-of-merit

experiment	w_0	w_a	Ω_X	Ω_K	$\Omega_m h^2$	$\Omega_b h^2$	FoM
DETF Stage-II + Planck	0.12	0.52	0.012	0.0033	0.0012	0.00017	53.7
+ DES	0.092	0.39	0.0081	0.0027	0.00012	0.00017	75.1
+ Wiggle-Z	0.10	0.46	0.010	0.0028	0.00012	0.00017	62.4
+ BOSS	0.078	0.30	0.0067	0.0023	0.00011	0.00017	109.9

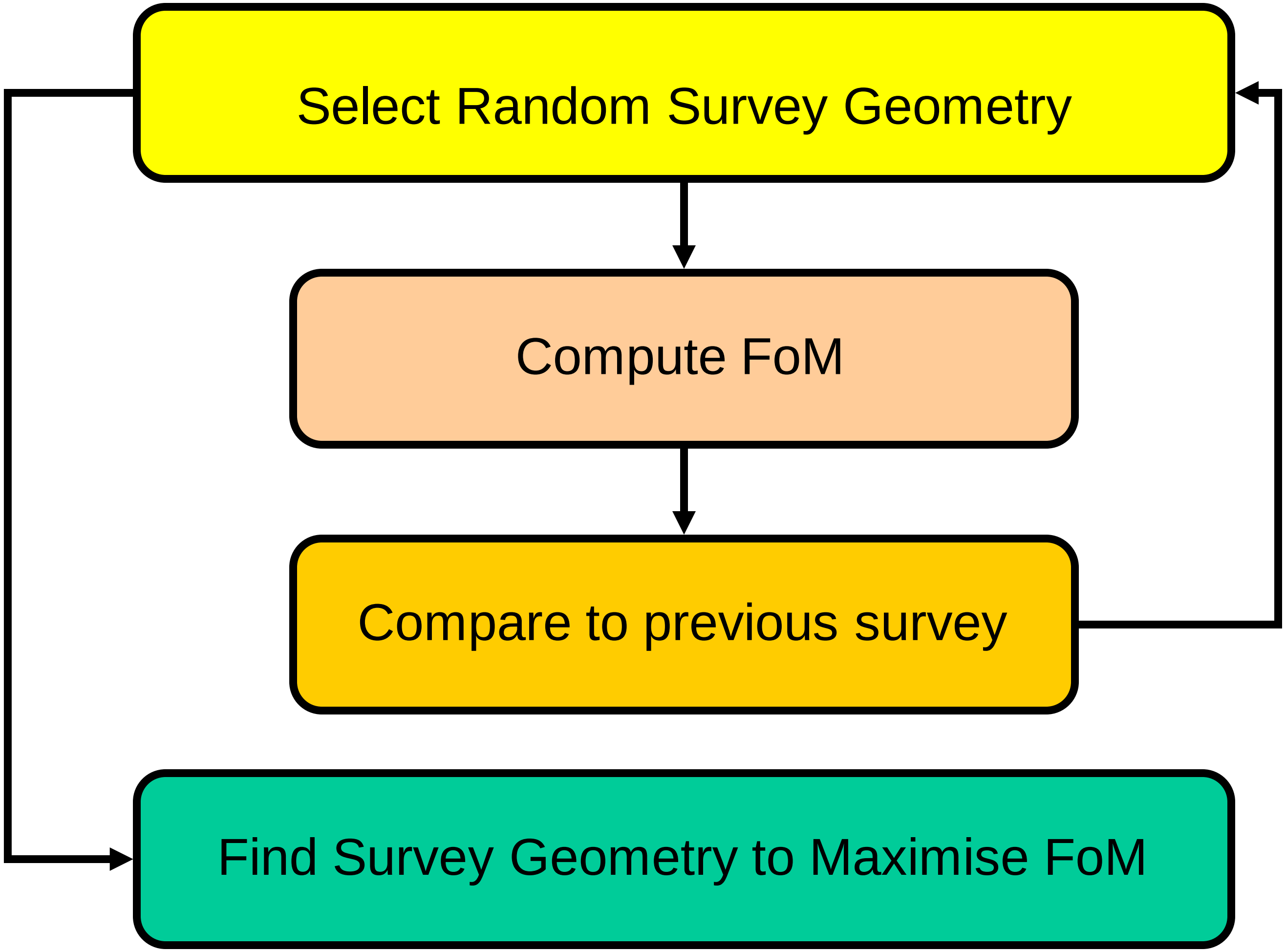
Table 1: Expected 1σ errors on cosmological parameters and the DETF Figure-of-Merit, calculated using the results predicted by the DETF for the combination of all Stage-II experiments and Planck results (top row: see text for details). These constraints then form the prior, and are combined with predicted distance-scale measurements from BAO measurements for either the DES, Wiggle-Z or BOSS (bottom 3 rows).

Effectiveness

- The errors on w (and so the FoM) of a survey depends on the fiducial cosmology.
- And even the conclusions that you draw from the data may change with the cosmology



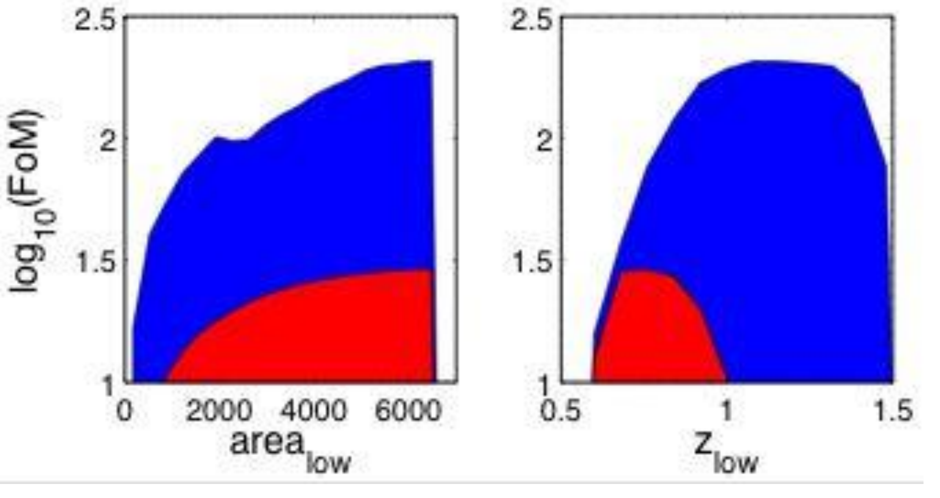
Optimisation Process



Single bin: z vs. area

- Input galaxy population affects optimal survey
  - Blue galaxies favour higher redshift bin (z~1) than fiducial (z=0.9), while red galaxies favour lower (z~0.8)
- Optimisation seeks to maximise area and minimise exposure time

Single bin at low redshift
• total time = 1500 hrs
• redshift range and area allowed to vary



Summary

- The SDSS and 2dF Galaxy surveys have demonstrated that Baryon Acoustic Oscillations can be used to measure the size and expansion rate of the Universe
- Future galaxy redshift surveys will be able to measure BAOs to probe the properties of the dark energy
- Constraints on DE from BAOs may not be as strong as those from other sources (e.g. Supernovae, Weak Lensing) but they provide a useful (and relatively clean) cross-check of results from other experiments/surveys.